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HYPERSONIC GLOBAL STRIKE

FEASIBILITY AND OPTIONS

by

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A Research Report Submitted to the Faculty

In Partial Fulfillment of the Graduation Requirements

15 February 2012

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Biography

Lt Col Letsinger is a fighter pilot with over 1500 hours in the F-15C and F-22, including combat time in various operations over the last 19 years. Lt Col Letsinger has served in four operational fighter squadrons, on the HAF Staff at SAF/AQPF as an acquisition Program Element Monitor, and was Commander of the 49th OSS, Holloman AFB. He has completed all levels of PME and has earned multiple advanced degrees.

Abstract

This paper explores the feasibility of hypersonic weapons and aircraft as global strike options in the 2035 timeframe. The paper proposes there are currently two limitations or gaps in U.S. prompt global strike capabilities; timeliness, and increasingly the ability to gain access to the highly-defended target area. Additionally, the USAF has a long history of using advanced technology to stay ahead of the threat defense systems and gaining access to target sets, and by 2035, anti-access and area denial (A2/AD) technologies will increasingly threaten the USAF ability to hold any target on the globe at risk. Therefore, given the fact that technologies will continue developing to diminish and deny the advantages of stealth and space assets, could speed once again allow access to denied, heavily defended targets and close the gap for prompt global strike by 2035?

The analysis begins with a brief overview of past hypersonic programs and reveals the lack of coherent government policy or USAF confidence in future military utility for hypersonic weapons or aircraft. The paper explores evidence that recent developments in threat radars along with future predictions for processing power and passive detection techniques will diminish the inherent advantages of stealth. Additionally, the Long Range Strike (LRS) family of systems, most likely the main global strike option in 2035, does not provide a prompt global strike solution, and a subsonic bomber could still be denied entry to some future A2/AD environments. After a thorough operational analysis of future concepts and a look at the current advances in hypersonic technology, this paper concludes there are feasible military missions for hypersonic cruise missiles and aircraft in the 2035 timeframe. Hypersonic missiles and strike or reconnaissance aircraft could fold into the LRS family of systems; providing deterrence, prompt conventional global strike, HDBT attack, and critical ISR missions in A2/AD environments.

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Introduction

Shortly after the 9/11 attacks, U.S. intelligence sources found Osama Bin Laden's location. President Bush had a brief opportunity to eliminate America's most wanted terrorist, but quickly learned our military could not strike this high-valued target in minimum time.[1] His only option was launching an Intercontinental Ballistic Missile (ICBM) or Sea Launched Ballistic Missile (SLBM), which was out of the question. This illustrates the gap in America's ability to perform conventional Prompt Global Strike (PGS), and hold any target on the globe at risk. Since then, Presidents Bush and Obama have made it a top priority to find solutions for the PGS problem.[2]

Definitions of prompt global strike ranging from 30 minutes (ICBM average time of flight) to a few days are being discussed by analysts, depending on the target and mission requirements. In this paper, "prompt global strike" is defined as "less than 8 hours from the time of the President's decision to launch to until weapon detonation or military action on a strategic target." This definition includes prompt reaction to strike any target on the globe, such as Weapons of Mass Destruction (WMD) processing facilities or fleeting mobile targets such as missile defense systems, or terrorists.

The USAF has a long history of using advanced technology to stay ahead of threat defense systems and gain access to target sets. In the Cold War, speed allowed aircraft like the SR-71 and B-58 to out-run the threat, providing Intelligence Surveillance and Reconnaissance (ISR) and global strike options. Threat radar and aircraft systems soon caught up however,

[1] National Geographic Video, "Inside America's Secret Weapon, (DARPA)," Dr. Steven Walker, Dept. Director of DARPA Tactical Technology office at the time, stated in an interview in National Geographic video: stated that shortly after 9/11word came down from the top that we needed a system that could get places fast and strike high value targets…This spawned the HTV-3X Blackswift project explored later in this paper.
[2] Woolf et al, "Conventional Prompt Global Strike and Long-Range Ballistic Missiles: Background and Issues, " 1.

challenging fast-moving aircraft; rendering the B-58 obsolete and limiting the SR-71 mission.[3] The USAF transitioned to Electronic Counter Measures (ECM) and air superiority support aircraft to penetrate highly-defended airspace. Eventually stealth and space technology regained our unfettered access to conduct ISR or strike nearly any target on the globe. Our stealth advantage lasted for many years, but is now insufficient for PGS.

There currently are two limitations in our PGS options: timeliness, and increasingly, access to highly-defended target areas. Without forward basing, B-2s require many hours to fly from CONUS to target.[4] Furthermore, emerging counter-stealth technologies will soon deny access to certain target sets. Given a future where stealth and space technology are diminished or denied, could hypersonic technologies re-enable speed to gain access and provide PGS options for the President by 2035?

This paper explores hypersonic weapons or vehicles as PGS options in 2035. Chapter one reviews the history of hypersonic research and how this elusive technology evolved. Chapter two explores how evolving technology could diminish stealth and space capabilities by 2035. Chapter three reviews the current global strike solution road map, namely the Long Range Strike (LRS) family of systems, and chapter four takes an operational analysis approach to survivability of hypersonic vehicles in 2035 A2/AD environments. Chapter five highlights some technological challenges and reviews current hypersonic programs. Finally, chapter six provides conclusions and recommendations regarding the feasibility of hypersonic technology and the USAF hypersonic roadmap.

[3] Although the SR-71 remained in service until the late 1990s…however, double digit SAMs proved to limit its mission
[4] Air Force Fact Sheet, "B-2 Spirit," http://www.af.mil/information/factsheets/factsheet.asp?fsID=82. Range = 6,000 nm, cruise speed .85 Mach. The B-2 completed non-stop missions to Kosovo and Afghanistan. At this speed it takes a B-2 approximately 11 hours to reach 6,000 nm, and over 30 hours round trip from Whitman AFB to the Middle East AOR.

History of Hypersonic Research

Hypersonic speed is where the aerodynamic heating considerations become as significant as the aerodynamic and structural limits.[5] Scientists first raised the possibility of reaching hypersonic speeds above Mach 5 in the 1920-1930s.[6] At these speeds, air temperature changes the dynamics of flight. At hypersonic speeds below Mach 10, this phenomenon changes the magnitude of the forces generated by air on the aircraft.[7] At speeds above Mach 10, air molecules break apart creating an electrically charged plasma layer around the aircraft. Hypersonic speed is achievable via either rocket propulsion, or with air-breathing ramjet and scramjet propulsion, accelerating the aircraft once it achieves supersonic speed.[8] The USAF understood the utility of speed for aircraft survivability and began exploring possibilities in the early 1950s.

Early research programs began in the realm of supersonic aircraft that could out run and fly higher than any Soviet threat. The North American XB-70 Valkyrie was to be the AF's first supersonic nuclear-armed deep-penetrating bomber, reaching Mach 3 at 70,000ft.[9] Politics, cost, and perceptions of the effectiveness of new Soviet Surface to Air Missiles (SAMs) caused the program to be canceled in 1961. The B-58 Hustler, a smaller supersonic bomber was briefly operational in the 1960s using the XB-70 test engines. This

Figure 1: XB-70

[5] Hallion, "Hypersonic Power Projection," 9.
[6] Hallion, "Hypersonic Power Projection," 3.
[7] NASA.gov, "Hypersonics Index," http://www.grc.nasa.gov/WWW/BGH/lowhyper.html
[8] Hallion, "Hypersonic Power Projection," 9.
[9] National Museum of the Air Force Factsheet, "North American XB-70 Valkyrie," http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=592. The XB-70 was to be powered with six nuclear engines, and weighing over 500,000lbs. While two test models of the XB-70 were built, both operated on conventional jet fuel. Due to cancellation of the program before prototype testing was complete; the nuclear variant was never constructed.

Mach 2 aircraft was cancelled for the same reasons as its predecessor, but provided a foundation for subsequent super/hypersonic aircraft research.

During this same time, the U.S. explored how to put man into space via the X-15 program; evaluating materials and human factors of high-speed flight.[10] The rocket powered X-15 first flew in 1959 and eventually achieved speeds Mach 6.7 and 354,000ft.[11] Built with a nickel-based Inconel-X material which could withstand extreme heat, the program advanced research in materials, human factors, manned space flight, aerodynamic controls, and rocket propulsion.[12] The Air Force capitalized on this research to build the hypersonic Dyna-Soar space plane.

Figure 2: X-15

The Dyna-Soar was a hypersonic boost-glide weapon concept, with a variety of military purposes such as reconnaissance, bombing, satellite maintenance, and offensive counter-space operations.[13] A precursor to the space shuttle program, the aircraft would be boosted into an exo-atmospheric ballistic trajectory by a Titan rocket.[14] Instead of falling back to earth like an ICBM, the Dyna-Soar use its wings and 17,000 mph speed to bounce off the atmosphere toward any terrestrial target at hypersonic speeds, then re-enter the atmosphere and glide to land under

[10] National Museum of the Air Force Factsheet, "X-15," http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=556 . The X-15, designed to provide data on material and human factors of high-speed, high-altitude flight, made the first manned probes into the lower edges of space. It was built for speeds of up to 4,000 mph and altitudes of 50 miles, but these goals were exceeded on numerous occasions. Several X-15 pilots earned "astronaut" rating by attaining altitudes above 50 miles. The X-15 flight program contributed significantly to the Mercury, Gemini and Apollo projects. The X-15 was carried aloft by a B-52 and was released at about 45,000 feet and 500 mph. Its rocket engine then fired for the first 80-120 seconds of flight. The remainder of the 10-11 minute flight was powerless and ended with a 200 mph glide landing on a dry lake bed.

[11] Naidu et al, "Resurrection in Hypersonics: Why What and When," 565. The record established by the X-15 was Mach 6.7 on 15 Oct 1967 at 354,200ft.

[12] Ibid, 565. The X-15 was built with Inconel X; a nickel alloy capable of withstanding 1,200F, Inconel was also used on the Mercury, Gemini, and Apollo space capsules and a standard material for hypersonics for years to come.

[13] Jenkins et al, "American X-Vehicles," 27.

[14] Boeing.com history page, "X-20 Dyna-Soar Space Plane," www.boeing.com/history/boeing/dynasoar.html. The X-20 was to use graphite and zirconia composite materials.

pilot control.[15] Dyna-Soar's funding was diverted to the Gemini program in 1963, but it gave DoD experience in hypersonic piloted vehicle design and systems integration. [16] [17]

After a 20-year hiatus, interest in hypersonics resurfaced as the Reagan Administration sought to construct the X-30 National Aero Space Plane (NASP).[18] NASP was a Single Stage to Orbit (SSTO) concept vehicle using scramjet engines, titanium and carbon-based composite materials.[19] Rising payload requirements increased NAPS costs, eventually cancelling the program.


Figure 3: Artist concept of NASP

In its wake came a more modest unmanned concept called the Hypersonic Systems Technology Program (Hy-Tech).[20]

Hy-Tech's program goal was to build a scramjet capable of Mach 8 for 12 minutes duration by 2000.[21] Although not met, Hy-Tech's technologies led to development of NASA's hydrogen powered X-43A "Hyper X", which was the first scramjet-powered vehicle to reach Mach 9.8 in 2004. [22] [23] This program was also cancelled, but paved the way for the ongoing X-51 Wave Rider program and the DARPA led Falcon

Figure 4: X-43A on a Pegasus Missile, carried by a B-52

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[15] Jenkins et al, "American X-Vehicles," 27.
[16] Boeing.com history page, "X-20 Dyna-Soar Space Plane," www.boeing.com/history/boeing/dynasoar.html
[17] Hallion, "Hypersonic Power Projection," 12.
[18] Hallion, "Hypersonic Power Projection," 14.
[19] Jenkins et al, "American X-Vehicles," 38. NASP had its roots in a classified DARPA program called Copper Canyon, which looked at developing a Single Stage to Orbit (SSTO) vehicle reaching speeds of over Mach 20
[20] Ibid 38. DOD leaders wanted the jet to have a crew of two and small payload for a possible penetrating bomber which drove the size and cost up for a technology demonstrator.
[21] Seebass et al, "Review and Evaluation of the Air Force Hypersonic Technology Program," 12, 26. The choice of Mach 8 appears to be driven by studying the upper limits of hydrocarbon-fueled missile. Funding was consistently shortfalled each year by Congress
[22] Global Security.org, "Hy-Tech, (Hypersonic Technology)," 1. www.Globalsecurity.org/military/systems/munitions/hytech.html Talks of Hy-Tech advances leading to NASA's hydrogen powered X-43A
[23] NASA.gov "X-43 Raises the Bar," 1. http://www.nasa.gov/missions/research/x43-main.html. Guinness World Records recognized NASA's X-43A scramjet with a new world speed record for a jet-powered aircraft - Mach 9.6, or nearly 7,000 mph. The X-43A set the new mark and broke its own world record on its third and final flight on Nov. 16, 2004. It was boosted by a modified Pegasus rocket which was launched from a B-52 at 13,157 meters (43,166 ft.). After a free flight where the scramjet operated for about 10 seconds, the craft made a planned crash into the Pacific Ocean off the coast of southern California. In March 2004, the X-43A set the previous record of Mach 6.8 (nearly 5,000 mph). The fastest air-breathing, manned vehicle, the U.S. Air Force SR-71, achieved slightly more than Mach 3.2. The X-43A more than doubled, and then tripled, the top speed of the jet-powered SR-71.

project.[24] In 2007, Falcon introduced a possible fighter-sized hypersonic test vehicle as a replacement to the SR-71, the HTV-3X Blackswift.[25] Lacking confidence, Congress cancelled Blackswift in 2008.[26] Currently funded hypersonic programs include: DARPA's HTV-2 ballistic missile powered boost-glide vehicle, the NASA/USAF X-37 Orbital Test Vehicle, and the US Army's Advanced Hypersonic Weapon (AHW) program. I will explore these programs later in this paper.


Figure 5: Artist concept of Blackswift (HTV-3)

A Day Without Stealth?

From the Vietnam War through the 1980s, the USAF relied on air superiority fighters, multi-role aircraft, Electronic Attack (EA), and mass fire power to overwhelm threat defenses. The emergence of Low-Observable (LO) technology in the mid-1980s with the F-117 again allowed aircraft access to heavily defended target sets. At that time, stealth materials and speed did not mix very well; stealth was less expensive and hypersonic technology seemed 20 years away.

During the 1980s and 1990s, the USAF used LO technology to penetrate highly-defended areas, and speed became less important for survivability. Using reflective material and airframe shaping, LO techniques delay enemy radar detection, minimizing the threat operator's time to engage. However, by 2035 improved computer processing power may enable technologies to

[24] Air Attack.com, "DARPA Falcon Project," http://www.air-attack.com/page/32/USAF--DARPA-FALCON-Program.html. The DARPA led Falcon project began in 2003 and is looking at prompt global strike options with hypersonic weapons and cruise aircraft.
[25] Trimble, "DARPA cancels Blackswift hypersonic test bed," http://www.flightglobal.com/news/articles/videos-darpa-cancels-blackswift-hypersonic-test-bed-317382/
[26] Warwick, "DARPA Cancels Hypersonic Blackswift," http://www.aviationweek.com/aw/generic/story_channel.jsp?channel=defense&id=news/BLACK101308.xml. In 2007 both Boeing and Lockheed were teamed to build a technology demonstrator, using a high Mach turbojet and dual-mode ram/scramjet. The fighter-sized remotely piloted aircraft would use a turbine engine for takeoff to accelerate the aircraft to Mach 4, where the ram/scramjet takes over. The program was canceled in early 2008 due to lack of confidence from Congress.

find, track, and kill stealth aircraft across the electromagnetic spectrum.[27] Future radar technology may be the most detrimental threat to stealth.

Advances in processing power may enable better tracking systems for long-wavelength radars that reduce the historical LO technology advantage. We know very high frequency (VHF), and ultra-high frequency (UHF) long-range air defense radars can see stealth aircraft at great distances, because LO techniques are targeted towards X-band target-tracking radar systems.[28] As the longer wavelength reflects off an aircraft, it significantly increases the Radar Cross Section (RCS), which enables VHF and UHF radars to detect stealth aircraft at further distances than fire-control X-band radars.[29] Historically these radars have poor resolution and cannot provide accurate target tracking data. However, Russia and China have both made considerable efforts to improve long-wavelength radar. New Russian models like the Nebo surface vehicle unit, a VHF adaptive electronically steered array radar, likely presents a

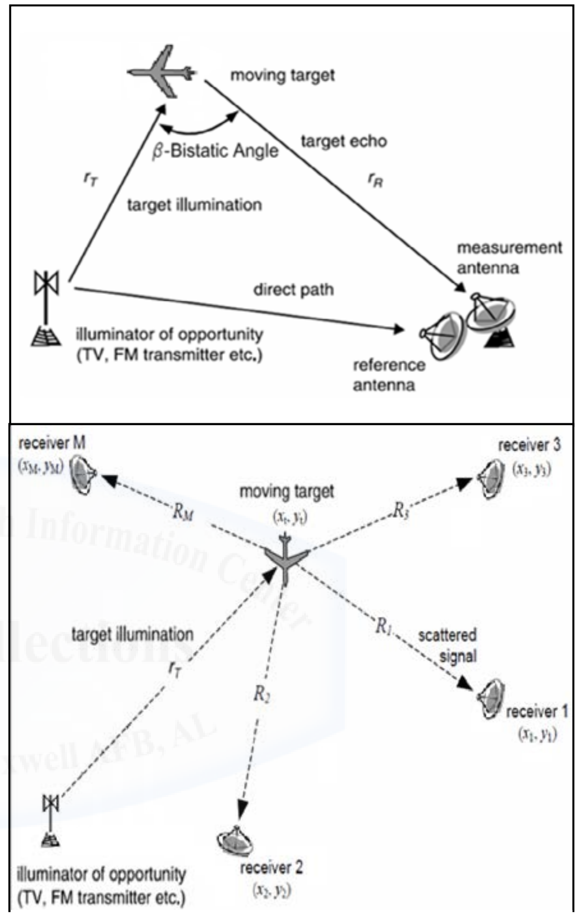

Figure 6: Bi-Static, Multi-Static Radar systems

[27] Computer History.com, "1965 - "Moore's Law" Predicts the Future of Integrated Circuits http://www.computerhistory.org/semiconductor/timeline/1965-Moore.html Moore's Law states that the number of transistors on a given chip can be doubled every two years--has been the guiding principle of progress in electronics and computing since Moore first formulated the famous dictum in 1965.

[28] Westra, "Radar Versus Stealth," 138. Most LO techniques are designed to defeat acquisition and fire control radar in the X band, which uses centimeter wavelength. VHF and UHF band radar uses decimeter to meter-long wavelength. The RCS of an aircraft increases as the wavelength of the illuminating radar increases.

[29] Ibid139. Author cited this from David Lynch, Introduction to RF Stealth (Raleigh, NC, SciTech 2004)

significant counter-stealth capability.[30] By 2035 other technology advances could leverage this capability.

Another counter-stealth technology is Passive Coherent Location (PCL). What makes PCL radars unique is they do not have dedicated transmitters. The system uses multi-static receivers from third party transmitters in the environment, and measures the time-difference-of-arrival between the reflection from the transmitter and signal reflection from the aircraft to determine bi-static range.[31] In principle PCL systems can detect all targets interacting with the electromagnetic field, using reflection from FM radio towers, TV/HDTV, and Cellular transmissions.[32] While conventional radar is vulnerable to attack by electronic warfare and anti-radar missiles, passive radar is covert and capable of long-range detection.[33]

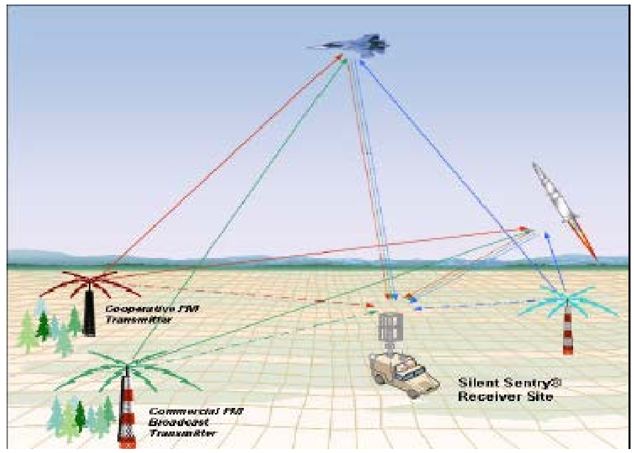

Figure 7: Silent Sentry PCL system

Currently many countries are fielding PCL radar systems such as the Russian VERA-E, which is said to be the only system that can detect the B-2.[34] Systems like Lockheed Martin's Silent Sentry, the British CELLDAR, and Thales-Raytheon's Homeland Alerter are also fully developed PCL systems.[35]

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[30] Westra, "Radar Versus Stealth," 139.
[31] Global security.org, "Passive Coherent Location," 1. http://www.globalsecurity.org/military/world/stealth-aircraft-vulnerabilities-pcl.htm
[32] Ibid 1.
[33] Westra, "Radar Versus Stealth," 139.
[34] Global security.org, "Passive Coherent Location," 1. http://www.globalsecurity.org/military/world/stealth-aircraft-vulnerabilities-pcl.htm
[35] Westra, "Radar Versus Stealth," 140.

Other interesting advances in radar technology include Active Electronically Scanned Array (AESA), Smart-L 3D, and Over-the-Horizon (OTH) long-range radars.[36] AESA radars like those used in the F-22, B-2, and F-35, are capable of passively tracking targets before the system emits radar energy; allowing targeting without illuminating the threat aircraft.[37] Increased processing capacity will allow AESA radars to use less power and find LO targets at longer ranges. Thales Company developed the (Signal Multi-beam Acquisition Radar for Targeting) SMART-L 3D naval long-range surveillance radar. This system stacks 24 phased arrays to project multiple L-band beams and develop accurate 3D target information.[38] Thales reports the system automatically detects targets out to 400 km, and detects LO targets and cruise missiles at medium range.[39] OTH radars, used since the 1950s, bounce long-wavelength radar energy off the ionosphere to see "over the horizon" tracking targets out to 3,000 miles. Many countries, including the U.S., field OTH radar systems, and Australia claims to have anti-stealth capabilities.[40]

Figure 8: SMART-L radar

Along with passive radar, emerging technologies look to exploit the IR and visible spectra. Stealth aircraft produce an intense heat signature in the aircraft exhaust, especially in afterburner. Highly sophisticated Infrared Search and Track (IRST) systems are employed by many modern

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[36] THALES Group.com "SMART- L 3D Long range surveillance radar," www.THALESgroup.com/SMART-L 1. Article states, Signal SMART-L is a 3D multi-beam radar designed to provide long-range air & surface surveillance and target designation. Operating in L-band, SMART-L provides a very long-range coverage (400 km radius) as well as 70° of elevation. State-of-the-art technology, combined with refined signal processing, SMART-L guarantees excellent performance, especially against stealthy targets in a littoral environment. SMART-L's high sensitivity allows for the early detection and tracking of very small aircraft and missiles. Recent tests with SMART-L equipped with the recently developed Extended Long Range module were highly successful. Thanks to the ELR module, SMART-L's already impressive range can be substantially increased.

[37] Interview with Jason Shroyer, Air Defense Technology Analyst, NASIC/ACIM (10 Nov 2011), and his briefing Counter Low Observable (CLO) Efforts, 22 Nov 2011, Slide 6. The digitization of detection assets and available processing power has presented opportunities to use more sophisticated processing techniques to improve detection/tracking capabilities…Increased sensitivity = track before detect (AESA Radar), Correlate before detect (Networked Radars).

[38] THALES Group.com "SMART- L 3D Long range surveillance radar," www.THALES group.com/SMART-L

[39] Ibid.

[40] Everything Explained.at, "Over-the-horizon radar explained," 1. http://everything.explained.at/Over-the-horizon_radar The Australians make this claim based on the Jindalee Operational Radar Network (JORN). See; Samuel B. (Bren). Cole grove. Project Jindalee: From Bare Bones To Operational OTHR. IEEE International Radar Conference - Proceedings. 825-830. IEEE. 2000. 2006-11-17.

threat aircraft like the SU-30. NASIC analysts believe these systems may be integrated into medium and even long-range SAM batteries by 2035.[41] These IR/electro-optical (EO) systems search and track with high magnification optics exploiting the IR and visible spectra.[42] Although potentially obscured by weather and vulnerable to laser attacks, they could provide another defensive layer to detect stealth aircraft.

Advances in millimeter-wave (MMW) technology also allow detection of stealth aircraft. This technology uses radiometric signatures naturally emitted by all objects to image and track targets. The waveform can be transmitted by radar, and could process returns to cue a missile system.[43] MMW systems like A-64 Apache Longbow can penetrate clouds and low-visibility, however, like EO/IR sensors they cannot provide overall surveillance pictures that radars can. Even so, multi-spectral systems integrated with robust IADs in 2035 could provide another means to target stealth aircraft.

All means to detect stealth are useless without a SAM system to track and kill LO aircraft. Current SAMs such as the Russian SA-20, SA 21, and the Chinese HQ-9, have powerful radars and advanced missile technology decreasing freedom of action for stealth aircraft.[44] The SA-21 tracks up to 100 targets out to 400 km, with improved capabilities against very small/low targets, cruise missiles, RPAs, and short/medium-range ballistic missiles.[45] The SA-21 also claims to

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[41] Interview with Jason Shroyer, Air Defense Technology Analyst, NASIC/ACIM (10 Nov 2011) and Shroyer, "Counter Low Observable (CLO) Efforts," 22 Nov 2011, Power Point Briefing Slide 3. IRSTS: MWIR/LWIR systems are currently predominately airborne, but countries like China and Russia are looking for ways to integrate ground based systems into future IADs.
[42] Westra, "Radar Versus Stealth ," 139
[43] Ibid, 139.
[44] Dr. Carlo Kopp, "Almaz-Antey 40R6 / S-400 Triumf Self Propelled Air Defense System / SA-21," 1. http://www.ausairpower.net/APA-S-400-Triumf.html. The SA-21 is also known as the S400.
[45] Ibid, 2. The radar can track 100 targets in Track While Scan mode, and perform precision tracking of six targets concurrently for missile engagements. data exchanges between the 92N6E Grave Stone and 30K6E battle management system are fully automatic

track small and very LO targets, thus able to intercept most conventional weapons like the JDAMM and SDB.[46]

Future SAM capabilities will continue to evolve. Russian defense Minister Anatoly Serlyukov stated the new S-500 equipped with AESA radar will track and kill targets beyond 500km.[47] He says, "The integration of defense systems will make it possible to intercept any targets at any speed, including hypersonic targets."[48] Jane's notes the S-500 will be both land and sea based and have similar performance to the U.S. THAAD and SM-3 systems.[49] However, OA experts interviewed are skeptical of many of Russia's claims.[50]

Integrated C2 networks strengthen IAD capabilities, and advances in data fusion over the next 20 years will only make them more difficult to penetrate. Dr. Dennis Bushnell, chief scientist at NASA's Langley Research Center, believes sensor and data fusion will continue to exponentially increase.[51] He says in the next 10 to 15 years, machine intelligence and signal processing will grow enough to network over 2 trillion sensors; synthesizing data from commercial, scientific, and military data streams.[52] Bushnell sees advances in quantum processing, low-power energy, Nano-technology, and inexpensive manufacturing, all combining to allow massive data fusion and huge increases in sensor ubiquity.[53] This globalization of data fusion could render no one invisible to radar, satellites, or many other technically advanced sensors in 2035.

[46] Dr. Carlo Kopp, "Almaz-Antey 40R6 / S-400 Triumf Self Propelled Air Defense System / SA-21," 3. The authors state that increased radar power-aperture product performance in both the 92N6E Grave Stone and 91N6E Big Bird increases the capability of the S-400 Triumf to engage low signature or stealth targets, but their cryptic claim of 50 percent of the engagement range remains difficult to interpret

[47] Russian Information Agency (RIA), "Russian Air Defenses Can Counter 'Even Hypersonic Missiles," United States Air Force Counter Proliferation Research & Education; Issue 959, 22 Nov

[48] Ibid, authors state the system will be running by Dec 2011 and will comprise of air defense, missile defense, missile early warning attack and space control systems.

[49] Janes.com, "S-500," 1. http://articles .janes.com/articles/Janess-Strategic-Weapon-Systems/S-500-S1000-Russian Federation

[50] Interview with OA expert who would not go on the record. He states that Russians claims to have the system up and running by the end of 2015 is not realistic. Also, the S-500 will be optimized for Anti-Ballistic Missile defense, focusing on ballistic hypersonic vehicles at extreme altitudes and not horizontal hypersonic weapons or aircraft. He states speed will remain a very real challenge to future systems including the S-500.

[51] Interview with Dr. Denis Bushnell, Chief Scientist, NASA Langley Research Center (10 Nov 2011), and Dr. Bushnell's brief, "Futures of Counter LO," slide 9.

52 Bushnell, "Futures of Counter LO," 9.

53 Ibid, Slide 10

Robust IADs in countries like China and Russia use data fusion today as they strive to cut kill chain latency.[54] One example is by using overlapping radars and integrated C2 to perform "plot fusion", where one operator may get a single radar return and as the aircraft travels, another radar site receives a single return. [55] Using C2 algorithms, the system fuses the plots, predicts the LO aircraft's path, and passes data to fire control radars. Some believe this is how Yugoslavia located and shot down the F-117 in 1999.

Another way to bolster C2 capabilities is with persistent on-station ISR. The combined DARPA and Lockheed Martin Integrated Sensor Is Structure (ISIS) program may provide such capability. ISIS is a large autonomous airship carrying a 6,000 m^2 Raytheon AESA low-power radar at altitudes above 70,000 ft.[56] If proven viable, ISIS could revolutionize C2 capabilities and replace legacy systems like AWACs, which are now pushed further from the fight by enemy threats. ISIS, combined with other integrated overlapping IADs may reduce latency issues, accelerating the kill chain for 2035 threats.

Figure 9: ISIS concept

Combining all the data reveals a gradually diminishing advantage of stealth over the next 25 years. Many of these technologies are in development today, and with evolutionary increases in technology, may prove to successfully counter stealth. If we see revolutionary changes, as prescribed by Dr. Bushnell, the threat landscape will surely deny the advantages of Stealth.

[54] Targeting or kill chain time is from first detection to initial ID to first shot on a target

55 Shroyer, "Counter Low Observable (CLO) Efforts," 22 Nov 2011, Slide 6, 7. All aspect LO is extremely difficult to maintain, therefore, methods for detection that look for a more favorable look angle or exploiting bistatic/forward scatter signatures could improve detection performance. Including: Networked air surveillance sensors (plot fusion), for Off-axis intercepts with datalink, and Cooperating triangulation with angle only sensors.

56 Defense Update.com, "ISIS," 1. defense-update.com/products/i/isis. Theoretically this airship could be airborne for up to 10 years, using combined X-band and UHF radar energy to track extremely small cruise missiles and unmanned at 375 miles

Any conclusions on the diminished value of stealth are not without controversy, and the defense industry seems extremely confident that stealth will preserve survivability.[57] In a recent study, the Center for Strategic and Budgetary Assessments (CSBA) argues stealth and EA will preserve U.S. global strike capabilities; suggesting the advantages of stealth are physics based, and will continue to provide high levels of survivability. [58] They recommend future systems concentrate on broad-band stealth techniques and EA to counter technological advances over the next 20 years.[59] Yet, telling indications show new technologies will not only undermine the stealth advantage by 2035, but also U.S. advantages in space.

[57] Dahm, "USAF Technology Horizons: A Vision for Air Force Science and Technology During 2010-2030," pg. 12. Low-observable technologies and the systems that employ them for long range penetrating and persistent strike are among the most distinguishing element of the Air Force. While advanced IADS may over time create an increasingly challenging environment for these critical systems, LO systems will remain essential for the ability they to penetrate defended airspace, for the sensitivities they demand in the air defense systems, and for the potential secondary benefits that this can create for other technology based capabilities.
[58] Gunzinger, "Sustaining America's Strategic Advantage in Long-range Strike," 7. The study cites the Secretary of the Air Force saying that PCL systems will probably not be able to overcome the false information they tend to generate and will be vulnerable to U.S. counter tactics. They also cite, IADs are vulnerable to cyber-attacks, and IAD C2 limitations make them susceptible to being overwhelmed by towed decoys and active jamming.
[59] Ibid, 38. Discusses the need for Broadband Stealth.

A Day Without Space?

It is well documented that space capabilities could also be contested, becoming a major challenge by 2035.[60] This paper does not detail developing anti-space technologies; I only mention the most relevant threats to highlight this fact below.

SPACE VULNERABILITIES	
1	Ground stations are vulnerable to symmetric and asymmetric attack
2	A nuclear detonation in space could destroy Low Earth Orbit satellite capabilities for all LEO space capabilities.
3	ASAT capabilities: Both U.S. the China have demonstrated this capability to kinetically kill a satellite with surface and air launched missiles.
4	Small lasers mounted on a Satellite tracker can dazzle the optics, blinding the satellite.
5	GPS signals can be easily jammed and by 2035, we very well may have to use alternative means for precision guidance.
6	Unmanned counter space systems. By 2035 unmanned systems like the X-37B OTV could be used for offensive counter space. Such vehicles could use small lasers or directed energy to take out enemy satellites.
7	Co-orbital systems could be launched by a missile to a threat satellites orbit and release parasite micro-sats to destroy or disable threat satellites.

Table 1: Vulnerabilities in Space[61]

[60] Grant, "Vulnerabilities in Space," 26. Author states that space is no longer a lonely place, 30 to 40 nations now have space capabilities.
[61] Table from Grant, "Vulnerabilities in Space," 27.

LRS Family of Systems

The near term solution to an aging bomber fleet and diminishing capability to hold any target on the globe at risk is the concept of the LRS family of systems. This family of systems will most likely be the main global strike option in 2035. A full history of this concept is in Appendix A. The LRS concept assumes that a bomber cannot solve the prompt global strike problem alone. It must be forward-based and augmented with stand-off weapons. Advances in hypersonic weapons and aircraft could provide critical capabilities for the LRS family of systems by 2035.

Advantages to Hypersonic Vehicles: Operational Analysis

The U.S. military could reap important benefits from affordable hypersonic systems because of their speed, altitude, and range. For example, a Mach 6 hypersonic missile (approximately 1 nautical mile/second) could strike a time-sensitive target 250 miles away in four minutes. Moving a mobile target in less than five minutes would be difficult.[62] Hypersonic missiles and vehicles fly at very-high altitudes, enabling them to overfly most SAM threats. Like stealth, hypersonic speeds shrink the newer threat system's OODA loop, or engagement time, making it extremely difficult for the AESA radars to find, track, and then shoot before the missile or aircraft travels out of range. Essentially, increasing speed has similar effects on survivability as reducing RCS, and significantly reduces exposure time to threat Weapons Engagement Zones (WEZ).[63] Finally, hypersonic vehicles cover great ranges in minimum time; making them optimal for ISR and strike missions.

[62] Seebass, et al. "Review and Evaluation of the Air Force Hypersonic Technology Program," Overview 1.
[63] Kenne, et al, "Committee on Future Air Force Needs for Survivability," 24. Using the Radar Range Equation, by increasing the speed by a factor of 10 is equivalent to decreasing the RCS by 40,000 to provide the same exposure time.

Hypersonic vehicles could overcome the constraints of distance, time, and defenses that limit conventional aircraft; conducting PGS or ISR in highly-contested airspace where space assets are denied and stealth advantages diminished. [64] In stealth-denied airspace, hypersonic aircraft may be the only way to deliver larger penetrating weapons to attack Hardened Deeply Buried Target (HDBT) strategic targets. Additionally, smaller hypersonic missiles could provide a stand-off capability for the LRS bomber and F-35 to strike mobile IAD and time-critical targets.[65]

Finally, in a day without space, hypersonic aircraft could be the only option to penetrate certain target areas, providing critical ISR to find/fix strategic targets. There is however some disagreement on how much speed is required to negate ever-improving threat A2/AD environments. See Appendix B for a more detailed look at Operational Analysis (OA) and the balance of speed vs. survivability. What follows are my overall conclusions from an OA perspective.

Operational Analysis Conclusions

Given the current threat missiles and detection range, it appears that Mach 5-6 with partial RCS reduction or a non-stealth aircraft flying at or above Mach 7 and above 100,000ft will be able to fly into current robust IADs with near impunity.[66] The figure below best depicts

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[64] Hallion, "Hypersonic Power Projection," 23. Author states, hypersonics overcomes the constraints of distance, time, and defense that already limit conventional aerospace power projection. It affords inherent rapid reach simply by the nature of its propulsion system. By definition, a hypersonic weapon moves at a minimum of about a mile per second, 60 miles per minute. In the time that an opponent begins shaping a response to a hypersonic attacker, the attacker can be already exploiting the effects of the first attack and moving on to other target sets.

[65] Some targets are time-critical by their nature. For example, in August 1998, the Clinton Administration executed conventional cruise missile attacks on Osama bin Laden's training camps in Afghanistan that probably "missed Bin Laden by a few hours." A hypersonic system would have struck the target in time. See: Hallion, "Hypersonic Power Projection," p. 24.

[66] This analysis is derived from data from the following sources (See Appendix B for further discussion). Seebass et al, "Review and Evaluation of the Air Force Hypersonic Technology Program," Appendix C, pg. 54, Ellrodt, Bernie. "The Value of Speed/Altitude and Signature for Survivability," Lockheed Martin Skunk Works Power Point Presentation, Oct 24, 2011.
Interviews with Mr., Bernie Ellrodt, Senior Manager Lockheed Martin Advanced Development Programs, Operational Analysis, Dr. Bradley Leland, Chief Engineer, Lockheed Martin Advanced Development Programs, Dr. Wesley Walker, MSIC Senior Analysts.
Tamplin, et al, "System and Operational Implications for Choosing the Best Speed for Global Missions." Kenne, et al, "Committee on Future Air Force Needs for Survivability

the balance between RCS, speed, and altitude versus probability of survivability (Ps) against today's most robust IADs.[67]

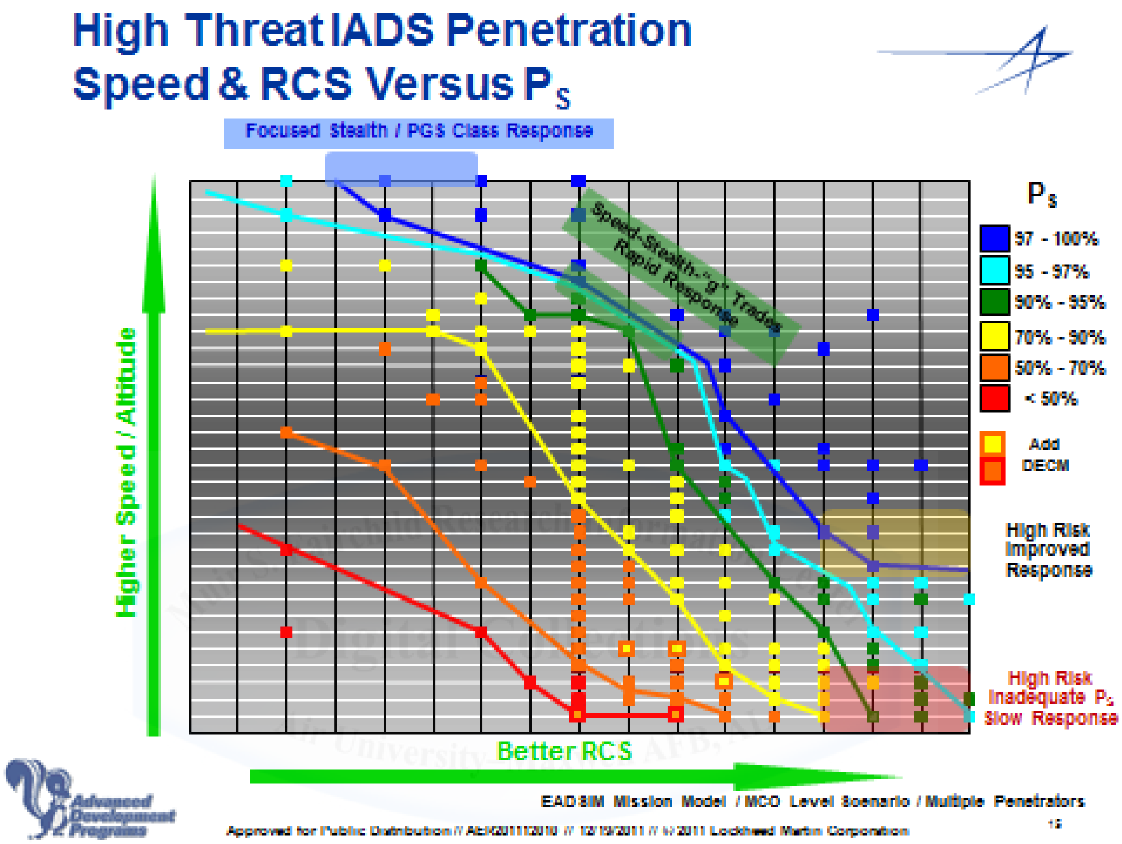

Figure 10: Skunk Works Speed & RCS vs. Survivability (Ps)

However, future technology developments will increase IAD detection ranges, allowing an earlier intercept on hypersonic aircraft as well. Even so, OA experts believe future SAM systems like the S500 and HQ-18/19 are mainly focused on anti-ballistic missile intercepts,

2 FAS.org, http://www.fas.org/nuke/guide/russia/airdef/s-300v.htm, Janes.com, Warfare.ru, http://www.warfare.ru/?lang=&linkid=1699&catid=264&topics=true&id=162, Australian Air Power.net, http://www.ausairpower.net/APA-Engagement-Fire-Control.html#mozTocId853844

[67] Ellrodt, "The Value of Speed/Altitude and Signature for Survivability," Lockheed Martin Releasable Power Point Presentation, Oct 24, 2011, Slide 15.

dealing with ballistic trajectories.[68] Additionally, air-defense missile kinematics above 100,000' may have reached a design limit, allowing hypersonic cruise missiles and aircraft to provide IADs with severe targeting challenges well into the future.[69] While long-range IR targeting may become a challenge, MISC experts deem the Directed Energy (DE) threat from China and Russia to be minimal by 2035.[70]

To conclude, this author's analysis suggests speeds above Mach 7 and altitudes above 100,000ft are required to penetrate future IADs. While LO technology and ECM/EA will continue to be important and provide design advantages against threats, RCS reduction techniques will most likely be required below Mach 7. Finally, as future SAMs and fighters develop, they will continue to challenge current and near future USAF force structure. Speed may become not only an option, but a necessity for certain ISR and strike missions.

Design Challenges for Hypersonic Vehicles

Risk and costs associated with the development of hypersonic air breathing systems increase significantly with speed. Technical problems increase as speed increases, mainly due to the severe heat created by hypersonic flight. The leading challenges are materials, propulsion and fuel limitations.

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[68] Interview with OA expert who would not go on the record. Also, from Janes.com, "HQ-18" Guidance is inertial with command updates and a semi-active radar terminal seeker. The maximum range is 100 km. The Chinese may be developing an improved version, but there has been no confirmation. An unconfirmed report in January 2010 stated that an intercept was made against an Anti-Ballistic Missile (ABM) target, and it is possible that this used an HQ-18 interceptor missile. (janes) http://articles.janes.com/articles/Janes-Strategic-Weapon-Systems/HQ-18-S-300V-China.html

[69] Interview with Mr. Bernie Ellrodt, Senior Manager Advanced Development Programs, Operational Analysis, Lockheed Martin , 14 Nov 2011.

[70] Interview Dr. Wesley Walker, Systems Engineer for Directed Energy Weapons, 9 Jan 2012. Approved Public Released Statement: Foreign countries are developing directed energy weapons (DEW) – laser and high power microwave weapons – for air and space defense. Statements from Russian and Chinese military leaders indicate the development of these advanced weapons is a priority for both of their countries. These efforts will probably result in deployed air defense and anti-satellite DEW systems within the next 20 years. Defense against ballistic missiles or hypersonic vehicles is a much more stressing application for DEW systems, as these weapons are designed to withstand heavy heat loads and are much more resistant to DEW effects. The deployment of DEW systems with this mission in the next two decades is questionable at best, and in reality probably unlikely.

Hypersonic Challenges			
Mach	Temperature/Material	Propulsion	Fuel
4	1,100 F, maximum limit for un-cooled titanium materials	Upper Ramjet Limit	Hydrocarbon
5-6	2,500 F Can use Inconel type materials,	Requires Scramjet	Hydrocarbon
8	4,200 F	Scramjet	Upper limit of hydrocarbon fuels

Table 2: Hypersonic Challenges[71]

Propulsion and Fuel Challenges

A missile or aircraft must accelerate to above Mach 3 before a ram/scramjet engine can engage and propel the vehicle to Mach 8, the limit of hydrocarbon fuels. Beyond Mach 8, liquid hydrogen is required for fuel. The initial speed requirement can be reached by either a rocket or a conventional jet-turbine engine.

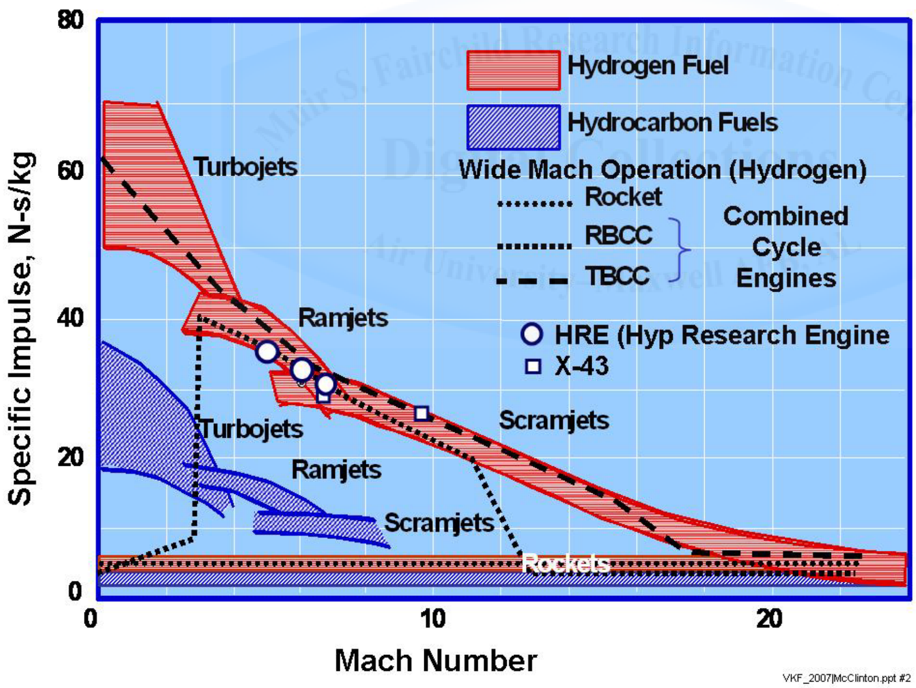

Figure 11: Hypersonic Propulsion Review[72]

The main concern for propulsion is heat. The temperature of oncoming airflow increases from about 1,100 deg F at Mach 4, to 2,500 at Mach 6, to 4,200 at Mach 8. Temperatures after

[71] Naidu et al, "Resurrection in Hypersonics: Why What and When," 569-570.
[72] McClinton, Charles R., "High Speed/Hypersonic Aircraft Propulsion Technology Development," 1-2.

combustion inside the engine are even higher, 5,000 deg. at Mach 8.[73] No known materials suitable for a scramjet can withstand this temperature without active cooling.[74] Additionally, at Mach 8 systems powered by a hydrocarbon-fueled scramjet will require endothermic fuel-cooled engine structures, requiring the use of liquid hydrogen which is expensive, difficult to store, and for which we have no aerial refueling capability.[75]

Material Challenges

Materials are a major challenge and can become very expensive. At Mach 4 and below, titanium-based materials, such as the material used on the SR-71 are sufficient.[76] From Mach 4 to Mach 6, vehicle structures must include materials such as Inconel. Above Mach 6 even these advanced materials must be actively cooled by using endothermic fuel-cooled metallic structures throughout the vehicle.[77] It may be possible to use non-actively cooled composites for speeds to Mach 6, allowing a 25 percent weight savings,[78] however, composites are much more expensive than Inconel to produce.[79] For this reason, the National Academy of Sciences recommended in 1999 that the Air Force forego composite-based Mach 8 systems and build a Mach 6 missile first. Additionally, a Mach 6 missile with the same engine could achieve 60 percent more range than a Mach 8 missile (780, to 1200), taking two minutes longer to reach the notional target.[80]

[73] Seebass, et al. "Review and Evaluation of the Air Force Hypersonic Technology Program," 1.
[74] Ibid, 1.
[75] Ibid, 3.
[76] NASA.gov Hypersonic Index. http://www.grc.nasa.gov/WWW/BGH/hisup.html
[77] Ibid. For Mach numbers greater than 5, the frictional heating of the airframe by the air becomes so high that very special nickel alloys are required for the structure. For some proposed hypersonic aircraft, the skin is actively cooled by circulating fuel through the skin to absorb the heat. Endothermic is defined as a heat-absorbing reaction or a reaction that requires heat.
[78] Seebass, et al. "Review and Evaluation of the Air Force Hypersonic Technology Program," 7. This could increase range, but composites are more expensive.
[79] Interview with Dr. Bradley Leland, Chief Engineer at Lockheed Martin Advanced Development Programs, 10 Feb 2012. He states, Mach 5 vehicles can use Titanium and Inconel based materials, however, for Mach 6, Inconel is less durable, lasting only a short time, and vehicles will require some composite treatments for durability. He says costs for Mach 6 materials are 5 times more than Mach 5. Above Mach 6, Space Shuttle type composites are required, adding another 2 to 4 times the cost to go from Mach 6 to Mach 7.
[80] Seebass, et al. "Review and Evaluation of the Air Force Hypersonic Technology Program," 7.

Plasma Interference and Weapons Employment Challenges

Two often over-looked challenges for hypersonic vehicles are the electrically-charged plasma that occurs at higher Mach numbers, and weapons employment. From Mach 10 up to orbital re-entry speeds, high temperatures cause the vehicle surface to produce an electrically charged plasma gas.[81] Plasma interferes with electronics making it difficult for ISR sensors to operate in a boost-glide reusable vehicle. Weapons employment is also a challenge, as it is difficult to model how weapons bay doors or the weapons themselves will behave at hypersonic speeds.

Cost Challenges

The above mentioned challenges increase cost. Similarly, requirements of range and payload also drive cost. One can nearly predict aircraft development costs in terms of dollars per pound; empty weight and speed are the most significant variables in cost.[82] In 1999, the Aeronautical Systems Center studied six design concepts for a future bomber, from a subsonic to an orbital Dyna-Soar type vehicle. Most of the data is export-controlled and detailed in Appendix C. Range and payload requirements caused the bombers to exceed 400,000 pounds; the study found cost increases as speed increases.[83] The study ranked the vehicles based on range, survivability, sortie rates, tanker requirements, and life cycle costs. Due to unknown technology risks, this study steered the USAF away from hypersonic systems, however AFRL

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[81] NASA.gov Hypersonic Index. http://www.grc.nasa.gov/WWW/BGH/shorth.html. Re-entry hypersonic flows are typically at Mach numbers from 25 to 10, with the vehicle constantly decelerating. The surface may be fully insulated, or it may undergo a physical change of state from solid to liquid to gas as it burns away. Because of the high temperatures, the gas is an electrically charged plasma. And because of the high altitudes where re-entry begins, the air is highly rarefied, having very low density. The force on the vehicle can be modeled using simple Newtonian flow.

[82] Hess & Romanoff, "Aircraft Airframe Cost Estimating Relationships," http://www.rand.org/pubs/reports/2006/R3255.pdf. Figure 15, pg. 45, and statements from interview with Dr. Jim Miller, AFRL

[83] Tamplin, et al, "System And Operational Implications For Choosing the Best Speed for Global Missions," 18.

and DARPA continue to look at the feasibility of hypersonic vehicles in current program research.

Current Hypersonic Programs Overview

The USAF is actively addressing challenges mentioned in the previous section to fill the current PGS capability gap. Dr. Steven Walker, deputy assistant secretary of the Air Force for science, technology, and engineering, recently unveiled the new Air Force hypersonic research roadmap that focuses on two parallel paths: an accelerated high-speed weapon to be fielded by 2016, and a reusable vehicle such as Blackswift, by 2021.[84] Walker believes this plan can leverage advances proven by the X-51 Wave-rider and X-37B Orbital Test Vehicle (OTV) and avoid the pitfalls associated with earlier more ambitious programs like the X-20 and NASP.[85]

X-51 Wave Rider

Recently the AFRL Propulsion Directorate's Hy-Tech program made some progress with scramjet engines and materials. The program developed a fuel-cooled structure using endothermic fuels and sponsored Pratt and Whitney to build a test scramjet engine operating on JP-7.[86] After a series of successful ground tests, the Boeing X-51 completed its first flight in May of 2010,

Figure 12: X-51 Wave Rider

[84] Norris, "USAF Revives Blackswift Hypersonic-Like Plan," 1. http://www.aviationweek.com/aw/generic/story.jsp?id=news/awx/2011/01/12/awx_01_12_2011_p0-281800.xml&channel=defense Dr. Walker unveiled the roadmap at the recent AIAA Aerospace Sciences conference in January 2011

[85] Ibid, 2. The weapons path would be fast-tracked, with development of a demonstrator over five years and first flight by October 2016. The more advanced element of the road map is Walker's call for a reusable demonstrator incorporating a turbine-based combined cycle (TBCC) system, as well as the ability to take off and land on a runway. As with the Blackswift project, the HSRFRV's TBCC will combine a high-Mach turbojet with a dual-mode ramjet/scramjet, the two sharing a common inlet and nozzle.

[86] Global Security.org,"Hy-Tech," http://Globalsecurity.org/military/systems/munitions/hytech.htm, Ground tests at 4.5 and 6.5 Mach in 2002-2005, the program teamed with Boeing to sponsor the X-51 program to flight test the scramjet.

achieving the longest scramjet-powered flight in history, 143 seconds at Mach 4.8 and 62,000ft.[87] This proved that fuel-cooled materials could withstand Mach 5 temperatures. The next step was to stretch the envelope to Mach 6. The second test flight in June of 2011 was less successful, failing after just 9 seconds.[88] Although the third test is not yet scheduled, the program manager remains optimistic.[89] Furthermore, Air Force Chief Scientist Mark Lewis believes more emphasis should be placed on building up experience using "weaponized" X-51s.[90]

The X-51 scramjet engine provides the basis for a high-speed strike weapon; but a reusable vehicle will need something different. For this AFRL proposes a turbine-based combined cycle (TBCC) system which combines a high-Mach turbojet with a dual-mode ram/scramjet; both sharing a common inlet and nozzle.[91] By 2015 scramjets could be scaled for testing, and requires additional funding. Another option is a Pulse Detonation Engine (PDE) combined with a

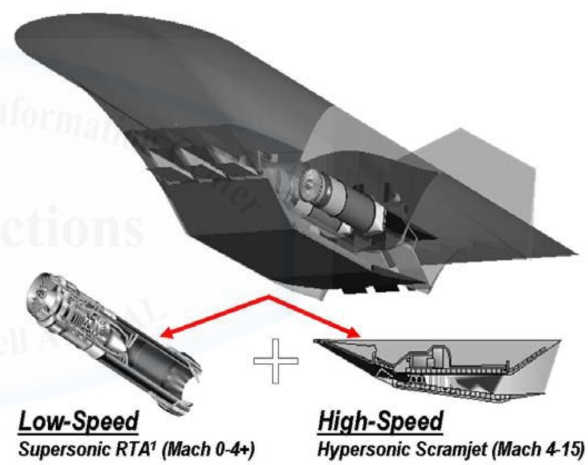

Figure 13: Typical TBCC Engine Concept[92]

[87] Air Force High Speed Science and Technology Plan, AIAA New Horizons Forum briefing 7 Jan 2011 Slide 4: Boost to 58,200 ft., Mach 4.85)--Engine ignition at 61,300 ft., Mach 4.74 --Successful scramjet light on ethylene --Successful transition to full JP-7 operation -- Climb and acceleration (~0.15g) to 62,300 ft., Mach 4.88 --Engine bay elevated temperatures -- Loss of telemetry at 210 seconds as Vehicle still accelerated

[88] LA Times.com Technology, "Experimental X-51 WaveRider aircraft's flight was 'less than successful,' Air Force says," June 17, 2011. http://latimesblogs.latimes.com/technology/2011/06/x-51-waverider-hypersonic-air-force.html In the test that took place Monday, a B-52 took off from Edwards Air Force Base and flew to 50,000 feet near Point Mugu. After the rocket engine separated, just 9 seconds later a lapse in airflow to the jet engine caused a shutdown and the X-51 plunged into the ocean as planned.

[89] Space.Com, "Hypersonic X-51A Failure Perplexes Air Force," 27 July 2011, 1. http://www.space.com/12441-hypersonic-x51a-waverider-scramjet-failure.html The experimental craft's air-breathing scramjet engine then lit briefly on ethylene but failed to transition to its primary JP7 fuel, Air Force officials said. The X-51A attempted to restart but was unsuccessful. "Obviously we're disappointed and expected better results, but we are very pleased with the data collected on this flight," said Charlie Brink, the Air Force Research Laboratory's X-51A program manager, in a statement. "We will continue to examine the data to learn even more about this new technology," Brink said. "Every time we test this new and exciting technology, we get that much closer to success."

[90] Norris, Aviation Week.com, "USAF Revives Blackswift Hypersonic-Like Plan."

[91] Norris, Aviation Week.com, "USAF Revives Blackswift Hypersonic-Like Plan."

[92] McClinton, Charles R., "High Speed/Hypersonic Aircraft Propulsion Technology Development," 1-4.

scramjet.[93] While the X-51 and X-43 demonstrated some material progress, these flights were relatively short and more research must follow.

HTV-2, X-37B, and AHW

Falcon program's HTV-2 focuses in on PGS aspect of hypersonic flight, able to reach anywhere in the world in less than 60 minutes. This program aspires to increase the knowledge-base for long duration hypersonic flight.[94] The Lockheed Martin HTV-2 is a rocket launched remotely piloted aircraft that glides through the upper atmosphere at Mach 20.[95] Hypersonic glide allows HTV-2 to avoid overflying non-friendly nations in-route to targets. HTV-2 flight data allows better understanding of composite material requirements and Plasma interference. The program completed two flights; neither achieving the entire flight profile, losing control-signal after about 9 minutes. [96] According to program manager Major Chris Schulz, the program is in virtually uncharted territory; aerodynamic control is the key challenge, and he's optimistic a solution is near.[97] More flights are required to prove out the technology.


Figure 14: Artist concept of HTV-2

[93] Wikipedia.org, "Pulse Detonation Engine (PDE)," 1. http://en.wikipedia.org/wiki/Pulse_detonation_engine. PDE is a type of propulsion system that uses detonation waves to combust the fuel and oxidizer mixture. The engine is pulsed because the mixture must be renewed in the combustion chamber between each detonation wave initiated by an ignition source. Theoretically, a PDE can reach speeds of roughly Mach 5...
94 DARPA.mil, "Falcon HTV-2," http://www.darpa.mil/Our_Work/TTO/Programs/Falcon_HTV-2.aspx: Data from the program informs policy, acquisition, and operations decisions for future Department of Defense Conventional Prompt Global Strike programs. The ultimate goal is a capability that can reach anywhere in the world in less than an hour.
95 Ibid. At HTV-2 Speeds, flight time between New York City and Los Angeles would be less than 12 minutes. The HTV-2 vehicle is a "data truck" with numerous sensors that collect data in an uncertain operating envelope.
[96] DARPA.mil, "Falcon HTV-2," HTV-2 flew its maiden flight on 22 Apr 2010, collecting nine minutes of unique flight data, including 139 seconds of Mach 22 to Mach 17 aerodynamic data. Flight one achieved many "firsts": Deployed largest number of sea, land, air and space data collection assets in support of hypersonic flight test, Maintained Global Positioning System (GPS) signals while traveling 3.6 miles per second, Validated two-way communication with the vehicle, Verified effective use of the Reaction Control System (RCS). On the second test flight the Minotaur IV vehicle successfully inserted the aircraft into the desired trajectory. Separation of the vehicle was confirmed by rocket cam and the aircraft transitioned to Mach 20 aerodynamic flight. This transition represents a critical knowledge and control point in maneuvering atmospheric hypersonic flight. Nine minutes of data was collected before an anomaly caused loss of signal.
[97] Ibid. Here's what we know," said Air Force Maj. Chris Schulz, DARPA HTV-2 program manager and PhD in aerospace engineering. "We know how to boost the aircraft to near space. We know how to insert the aircraft into atmospheric hypersonic flight. We do not yet know how to achieve the desired control during the aerodynamic phase of flight. It's vexing; I'm confident there is a solution.

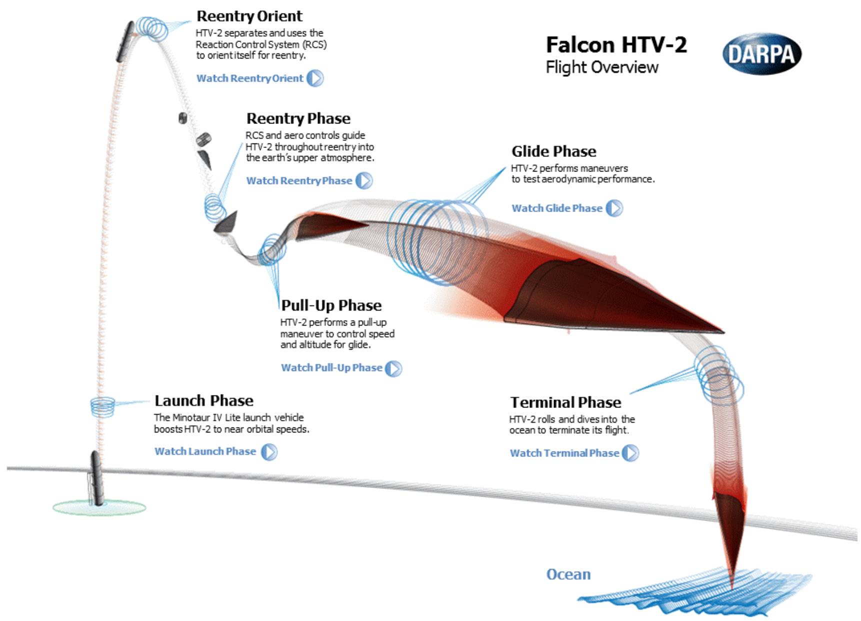

Figure 15: HTV-2 Flight Profile

Figure 16: X-37B OTV

Another current hypersonic program is the X-37B OTV program, similar to an unmanned version of Dyna-Soar. The OTV rides a booster rocket into orbit, then rendezvous with satellites to repair/refuel, and glides back to earth making a Space Shuttle type landing.[98] After two successful missions, an OTV is currently in orbit as of Feb 2012, and in the future could provide offensive PGS capabilities.[99] However, current space treaties prohibit the U.S. from weaponizing space with a "Rods-from-God" concept.

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[98] Air Force Factsheet, "X-37B Orbital Test Vehicle," http://www.af.mil/information/factsheets/factsheet.asp?fsID=16639 The X-37B Orbital Test Vehicle is the newest and most advanced re-entry spacecraft. Based on NASA's X-37 design, the unmanned OTV is designed for vertical launch to low Earth orbit altitudes where it can perform long duration space technology experimentation and testing. Upon command from the ground, the OTV autonomously re-enters the atmosphere, descends and lands horizontally on a runway. The X-37B is the first vehicle since NASA's Shuttle Orbiter with the ability to return experiments to Earth for further inspection and analysis, but with an on-orbit time of 270 days, the X-37B can stay in space for much longer. The Secretary of the Air Force stated that the OTV program would focus on "risk reduction, experimentation, and operational concept development for reusable space vehicle technologies." As part of its mission goals, the X-37 was designed to rendezvous with friendly satellites to refuel them, or to replace failed solar arrays using a robotic arm.

[99] Ibid. The Air Force's first X-37B, OTV-1, launched from Cape Canaveral Air Force Station, Fla., April 22, 2010 and performed a successful autonomous landing at Vandenberg AFB, Calif., Dec. 3, 2010, after approximately 91 million miles and 224 days, 8 hours and 24 minutes in orbit. Its payload could also support Space Control (Defensive Counter-Space, Offensive Counter-Space), Force Enhancement and Force Application systems

Another possible conventional PGS weapon is the AHW program. The U.S. Army Space and Missile Defense Command concept is a missile capable of attacking targets 6,000km away in less than 35 minutes.[100] Similar to HTV-2 but much slower, AHW built upon successful three-stage boost glide tests to successfully launch a glide vehicle in Nov 2011 in a non-ballistic trajectory, hitting a target over 2400km away.[101] Upon reaching the target AHW could maneuver, delivering 900lbs of "rods" impacting at Mach 4.[102] The USAF plans to leverage all current hypersonic research to develop a hypersonic cruise missile and aircraft.

Current USAF Hypersonic Roadmap

AFRL followed Dr. Walker's guidance and produced a comprehensive plan to develop technologies for a high-speed weapon and hypersonic aircraft demonstrator. Unlike past programs, this roadmap is less ambitious and depends on parallel research breakthroughs to help limit costs and provide solutions. Additionally, AFRL funded Boeing and Lockheed Martin to perform a feasibility study called the High Speed Mission Analysis Research program. They were tasked to perform OA on concepts for a hypersonic cruise missile and aircraft. This study helped refine the hypersonic roadmap, but is a proprietary controlled and cannot be included here. However, a source close to the program revealed, sensor technology is an important driver for achieving useful capability in high-speed aircraft. Also, the USAF must refine operational

[100] Grossman, Military.com, "Army Eyes Advanced Hypersonic Weapon," http://www.military.com/features/0,15240,121633,00.html, Jan 5, 2007. Author states and AHW weighs less than 40,000 pounds and measuring less than 35 feet -- is envisioned as a boost-glide weapon capable of attacking targets up to 6,000 kilometers away in less than 35 minutes, according to defense officials. The Advanced Hypersonic Weapon is inserted into the upper atmosphere with a two-stage rocket, where it separates and hypersonically glides to a designated target," The initial boost would get AHW to an altitude of about 300,000 feet, after which the system would glide en route to its target at approximately 150,000 feet, according to other sources. According to information paper circulated on Capitol Hill and obtained by ITP. "Due to technical advancements in guidance, space-based infrastructure, thermal protection materials and kinetic-energy warheads/fuses, it is now possible to develop a highly flexible, long-range, low-cost, strategic strike weapon.

[101] Morgan, "Department of Defense Announces Successful Test of Army Advanced Hypersonic Weapon Concept," Nov 17, 2011. http://www.defense.gov/releases/release.aspx?releaseid=14920. The Department of Defense is using AHW to develop and demonstrate technologies for Conventional Prompt Global Strike (CPGS). As part of the CPGS effort, the Defense Advanced Research Projects Agency conducted boost-glide flight tests in April 2010 and August 2011, results from which were used in planning the AHW flight test. The objective of the test is to collect data on hypersonic boost-glide technologies and test range performance for long-range atmospheric flight. Mission emphasis is aerodynamics; navigation, guidance, and control; and thermal protection technologies. The vehicle flew a non-ballistic glide trajectory at hypersonic speed to the planned impact location at the Reagan Test Site. Space, air, sea, and ground platforms collected vehicle performance data during all phases of flight. The data collected will be used by the Department of Defense to model and develop future hypersonic boost-glide capabilities

[102] Grossman, "Army Eyes Advanced Hypersonic Weapon," http://www.military.com/features/0,15240,121633,00.html

requirements such as air-refueling capacities and range requirements to scope design concepts into something practical. This source stated, “This is a hard problem, but we think we are getting closer to making a good business case for high-speed or hypersonic systems.”[103]

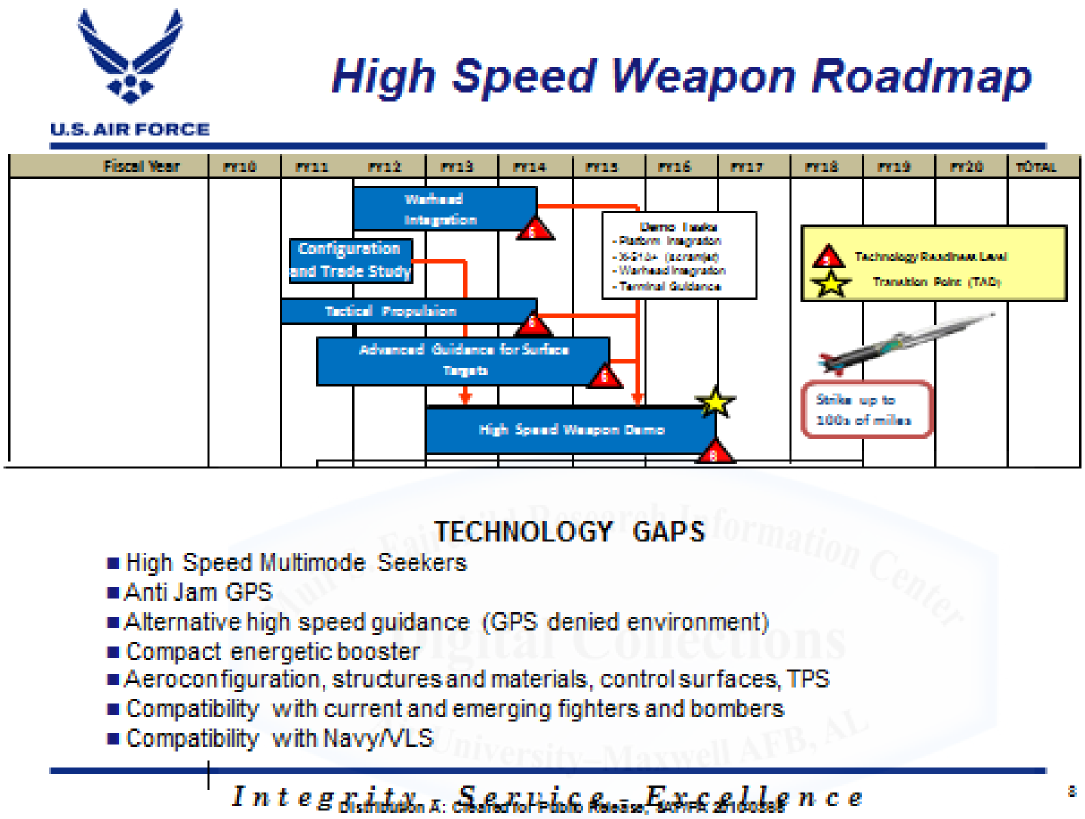

Figure 17: Hypersonic Roadmap: High-speed Weapon

103 Source close to the AFRL program who would not go on the record

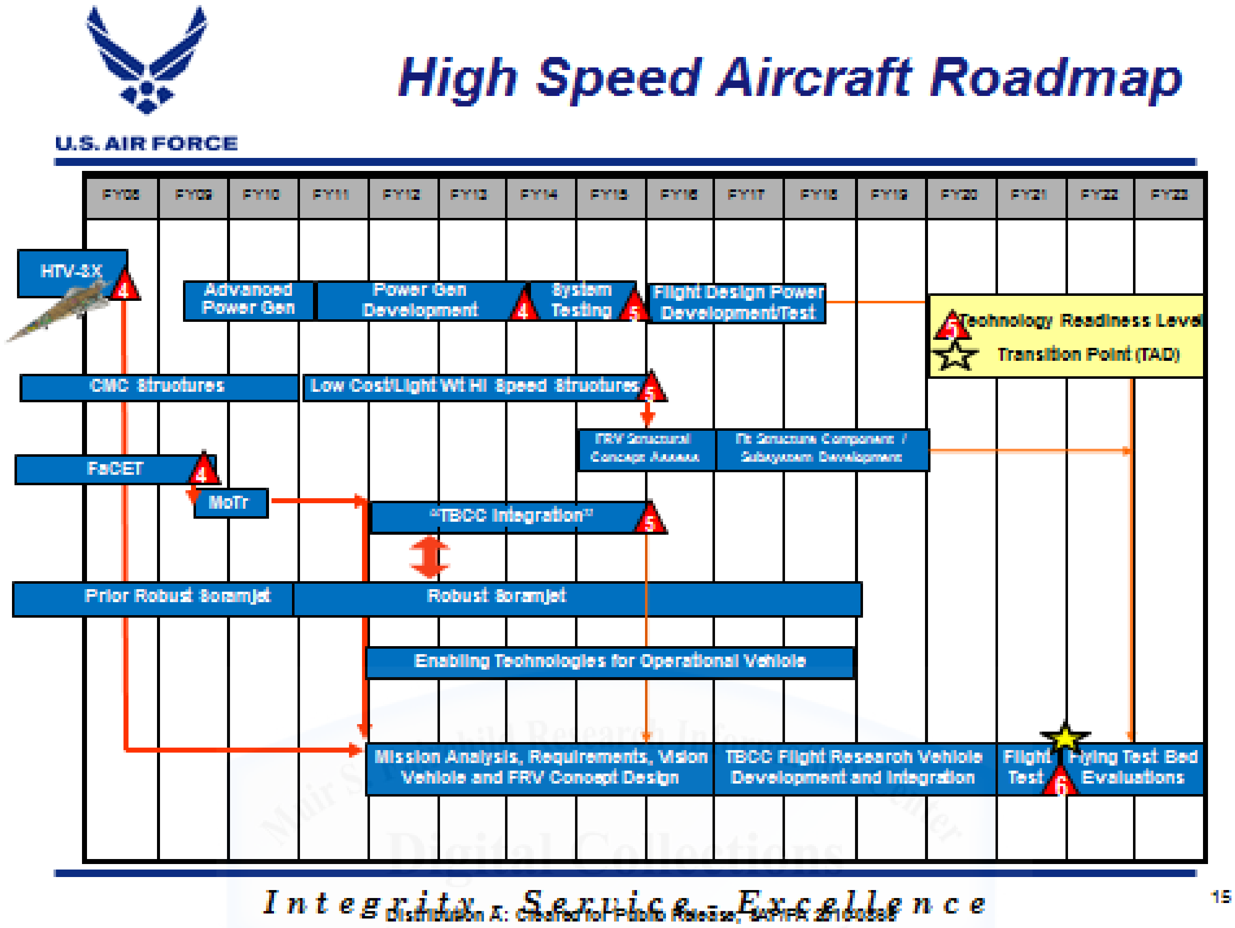

Figure 18: Hypersonic Roadmap: Aircraft

Conclusions and Recommendations

More than 40 years ago, the rocket powered X-15 achieved hypersonic speeds of over Mach 6. Since then, hypersonic programs have come and gone for one reason or another. Only in the past decade have research programs begun in earnest to solve some of the major technology challenges involved. To make plausible conclusions on the feasibility of hypersonic weapons and vehicles we must address the major counter-arguments proposed over the years.

The most prevalent counter-argument throughout the literature is that hypersonic technology is still 20 years away and unattainable. Many times scientists or politicians were unwilling to take risks, or other technology like stealth came along to diminish the relevance of

hypersonics. Although flight at high dynamic pressures, extreme heat, and other challenges are difficult, recent research is beginning to prove the technology is not unattainable. Despite some setbacks in the X-51 and HTV-2 flights, the Hy-Tech, AHW, and Falcon programs recently made some real breakthroughs in propulsion and materials.[104] For propulsion, the USAF timeline for the TBCC engine shows a turbine scramjet combined engine could be a reality by 2016. Also, emerging technologies like PDE engines could provide another avenue to reach the initial speed required for a scramjet to take over. For materials, experts from AFRL and industry are confident composite materials for Mach 7 flight are possible.[105] Thus we can no longer say the technology is unfeasible; meanwhile, competitors like China and Russia are pursuing hypersonic concepts with vigor.[106] It will however take robust R&D funding and willingness to take on some risk in order to make hypersonic vehicles a reality.

This leads to the second counter-argument to hypersonic technology; that it is too risky and too costly. This paper looked at the relationship of cost and weight related to air vehicles.[107] Not only size, but also increasing the speed of an aircraft increases the cost to a point (See Appendix A). Additionally, materials for Mach 7 plus vehicles are more expensive than Inconel/composite vehicles (Mach 6 and below) due to composite forging processes.[108] However, solutions exist to decrease costs of a vehicle in terms of size and materials. Many

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[104] Dr. Steven Walker, SAF/AQR Brief to AIAA, "Air Force High Speed Science and Tech brief," slide 5. X-51 first flight scramjet operating time was 4 times the total of all other scramjet flights in history. Falcon program has many firsts, HTV-2 was first to do a successful boost to glide to Mach 20 using new composite materials …DARPA website

[105] Interviews with sources close to HSMAR program who would not go on the record. On open source, the Ultramet company has in development materials that can withstand 3800 deg. F. For more see http://www.ultramet.com/ceramic_protective_coatings.html

[106] Richard A. Seebass, et al "Review of AF Hypersonic Tech," pg. 30. Russia invested heavily in advanced air-breathing missiles and fielded several operational ramjet-powered systems such as the SA-6, SS-N-22, and according to MSIC experts China and Russia are pursuing hypersonic cruise missile technology

[107] GAO Paper, "B-2 Bomber: Cost and Operational Issues (Letter Report, 08/14/97, GAO/NSIAD-97-181),"
"B-2," http://www.fas.org/man/gao/nsiad97181.htm, B-2 = 336,000 empty bomb bay, 376,000 fully loaded takeoff weight ,$737M 1997 dollars, = $1.01B today. From USAF FY 2011 Budget Estimates, "Aircraft Procurement Vol 1," http://www.saffm.hq.af.mil/shared/media/document/AFD-100128-072.pdf F-22 cost per unit = $150M, max Takeoff weight $83,500lbs and costs, only two data points, but one can extrapolate to say a new aircraft costs about $2 per pound.

[108] Interview with Dr. Bradley Leland, Chief Engineer at Lockheed Martin Advanced Development Programs, 10 Feb 2012. He states, Mach 5 vehicles can use Titanium and Inconel based materials, however, for Mach 6, Inconel is less durable, and lasting only a short time and vehicles will require some composite treatments for durability. He says costs for Mach 6 materials are 5 times more than Mach 5. Above Mach 6, Space Shuttle type composites are required, adding another 2 to 4 times the cost to go from Mach 6 to Mach 7.

think the range required for ISR or strike missions necessitates a 400,000lb class bomber with a large payload. However, a smaller fighter-bomber sized vehicle like the Blackswift concept, with enough payload for ISR equipment and a few smaller penetrating weapons or stand-off hypersonic missiles is a cheaper solution. For materials, experts at NASA believe revolutions in Nano and ceramic technology could yield lighter, stronger, cheaper heat resistant materials in the near future.[109] Also, Inconel materials used in the X-15 which withstand temperatures up to Mach 6, combined with composites in certain key areas provide a cheaper alternative for a smaller vehicle.[110] With some LO shaping and high-speed stealth materials, a Mach 6 vehicle could survive in future A2/AD environments. The drawback to this is increased range requirements to avoid known threats.

Another counter-argument is that stealth and EA/ECM will continue to allow survivability in any future A2/AD environment. Perception of the threat has always been a factor when speculating future capabilities, and this holds true for hypersonics. During the Cold War Airmen built up the Soviet SAM threat to be this 800ft tall monster, when in actuality they were not all that capable. Today the opposite is true, as some now downplay the 2035 threat and believe the LRS family of systems can continue to use stealth and EA/ECM/EP to gain unfettered access.[111] However, future developments in processing power, data fusion, and both active and passive radars are just a few ways stealth could be diminished. While Stealth and

[109] Dr. Charles Harris, AIAA SDM Conference "Opportunities for Next Generation Aircraft enabled by Revolutionary Materials." April 7 2011. Slide 3. Smart materials, agile manufacturing, and nanotechnology will change the way we produce devices while expanding their capabilities, the results could be astonishing. Slide 31, Boron Nitrate Nano Tubes properties allow increased thermal conduction (approx. 600 W/Mk) and radiation protection. Slide 40: Structural materials for airframe and subsystems: up to 2X reduction in structural weight can be achieved by carbon fiber reinforced polymers, metal matrix composites, and intermetallics; CNT composites offer as much as 10X weight reduction. Structural materials for propulsion components: ceramics may offer a factor of 2 gains in use temperature. BNNT exhibits thermal stability at 800C+ (1472F); CNTs are under development. ALSO: Ultramet.com, http://www.ultramet.com/ceramic_protective_coatings.html says Layered Hafnium Carbide/Silicon Carbide coatings are heat resistant up to 3800deg F.
[110] Interview with Dr. Bradley Leland, Chief Engineer at Lockheed Martin Advanced Development Programs, 10 Feb 2012. For a durable vehicle, Inconel plus some composites are required. However, this is 2 to 4 times cheaper than a Mach 7 vehicle which requires Space Shuttle like composite materials. He says low cost manufacturing techniques in the works at LM are key to enabling hypersonic aircraft.
[111] Gunzinger, "Sustaining America's Strategic Advantage in Long-range Strike," 35.

electronic capabilities will surely help the LRS bomber gain access to some A2/AD environments, they do not solve two difficult problems, distance and time.

The tyranny of distance and time will pose a challenge to any strike mission in Asia or the Middle East as more capable systems drive U.S. military force basing further away. The LRS solution is a subsonic bomber with most likely only two engines to keep costs down.[112] At .85 Mach, it takes 5.5 hours to travel 3000 miles, not accounting for any air-refueling requirements. A forward deployed bomber could possibly arrive on target in less than the proposed 8 hour PGS timeline requirement, but with limited fuel perhaps unable to penetrate the IADs. One possible solution is stand-off hypersonic missiles, able to reach the final 600 to 800 miles to a strategic/time-sensitive target.[113] Although hypersonic cruise missiles are viable for some targets, they carry a small warhead payload, and probably not viable for attacking HDBTs.[114] Hypersonic aircraft provide a possible solution because the aircraft's speed doubles its effective max range.[115] Thus, a smaller F-111 sized hypersonic vehicle could theoretically have more range than a larger LRS bomber, able to reach targets much quicker.

Despite apparent advantages, the final counter-argument discussed by some experts is that there is no viable military mission for hypersonic vehicles. Most agree hypersonic cruise missiles and HTV-2 or AHW type systems offer solutions for stand-off and conventional PGS. Some experts also agree hypersonic aircraft do not offer much military utility for time-sensitive targets.[116] By 2035 however, speed may become a requirement to overfly and outrun enemy

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[112] Author's speculation only, a 4 engine bomber would allow for twice the range, but at almost twice the cost due to added weight.
[113] Kenne, et al, "Committee on Future Air Force Needs for Survivability," 42. High-Speed weapons potentially add to overall system survivability by enabling attack of time-sensitive targets or targets outside the range of conventional glide weapons.
[114] Interview with Dr. Stephen Huve, Aerospace Engineer, AFRL Air Vehicles Directorate, High Speed Aerodynamic Configuration, 12 Nov 2011. He says a 2000lb payload drives the size of the missile to the size of an X-15 (small fighter).
[115] Interview with Dr. Denis Bushnell, Chief Scientist, NASA Langley Research Center (10 Nov 2011), and "Hypersonic Realities" slide 21.
[116] Watts, "Imperatives, Urgency and Options" CSBA, 2005, 74. Still, as attractive as hypersonic cruise may be to advance the state of aerodynamics and engine technology, a vehicle traveling at Mach 8 does not provide meaningful dwell or loiter. Bluntly stated, hypersonic offers little operational utility against problem of emergent/time-sensitive targets. These observations argue that the operationally useful speed regime for a future LRS system can be reduced to somewhere between Mach 0.7-0.9 (high subsonic) and less than. Also See: Hallion, "Hypersonic

fighter interceptors and SAMs. Stealth technology may become less effective and space assets easily denied. Hypersonic aircraft could become the only solution to penetrate IADs and attack HDBT strategic targets, or to provide much needed reconnaissance in A2/AD environments. And although hypersonic aircraft cannot loiter over a target area, I contend neither will the large LRS bomber, nor smaller stealthy RPAs by 2035.

Clearly, there are viable military missions for hypersonic vehicles. First, conventional PGS weapons like the AHW and HTV-2 could provide an additional deterrence option to compliment the Nuclear Triad against terrorist groups and countries producing/proliferating WMD. Additionally, these weapons avoid over-flight of non-friendly nations in-route to any global target in less than an hour.[117] Second, stand-off hypersonic missiles could enable LRS bombers and F-35s to attack enemy IAD systems and C2 targets quickly, allowing follow on SOF or conventional forces to penetrate and strike terrorist camps or other strategic targets. Third, much like the SR-71 before, small numbers of hypersonic reconnaissance/strike aircraft could perform niche ISR, and HDBT/strategic attack missions in A2/AD environments unreachable by the LRS bombers.[118] Together, these three different types of hypersonic systems could compliment the LRS family of systems and provide the President both deterrence and global strike options.

After exploring hypersonic technology, we clearly have a long way to go. Past trends reveal programs like NASP and Dyna-Soar quickly became too ambitious. These endeavors caused much skepticism and stymied progress for true technology advancement. That said I believe the current USAF hypersonic technology roadmap is on the right track. With proper

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Power Projection," 26. Author states, a hypersonic aircraft is probably not feasible, the need has not yet been defined sufficiently as to warrant its development.

[117] A HTV-2 type weapon traveling at Mach 20 could glide from the U.S., around the horn of Africa to reach a target in the Middle East or Russia in approximately 1 hour (ex. 16,000 miles = 80 minutes @ Mach 20)

[118] http://en.wikipedia.org/wiki/SR-7, 32 SR-71s were built, and in a similar niche mission, the USAF would need much fewer hypersonic aircraft than the 80-100 LRS bombers; reducing overall program costs.

funding the USAF could achieve a hypersonic cruise missile in five years, a demonstrator aircraft in ten years, and possibly a military ISR/Strike platform by 2030. From a holistic view of hypersonic research past present and future, here are some further recommendations for consideration.

OA, Weapons Integration, and Sensors

Extensive OA against possible future SAM systems and long-range IR capable threats is required to help refine speed/altitude requirements. Any "knees-in-the-curve" must be better defined, balancing speed and LO materials requirements.[119] Range requirements drive size, and OA experts must explore options for refueling and forward basing to reduce size and overall vehicle cost. More research is also required on Russia and China's ABM capabilities as a possible threat to hypersonic vehicles.[120]

Research in high-speed weapons employment and future HDBT penetrating weapons is a must. Parallel research into smaller weapons will reduce weapons payload requirements, keeping aircraft size down and reducing cost. One possible weapons solution is heavy tungsten metal rods, or "Rods-from-God," employed by a hypersonic aircraft, or shot from space by an X-37B against HDBTs.[121] Finally, sensors are a real challenge, and further research must focus on sensor integration for both Mach 7 and high-hypersonic HTV-2 type vehicles.

[119] More OA is needed to verify if Mach 7 plus is required, or if a Mach 5-6 platform with LO treatments for RCS reduction can survive. A Mach 5-6 materials are much cheaper, but that type of aircraft will have to avoid known threats, and maneuvering will decrease its combat range. Further research is required to explore these trade-offs.
[120] OA experts point out that most ABM systems are geared toward ballistic trajectories and not optimized for horizontal hypersonic vehicles at 100,000ft and this would still be a challenge in 2035. However, more research is required.
[121] Popular Science.com, "Rods From God," http://www.popsci.com/scitech/article/2004-06/rods-god. The concept of kinetic-energy weapons has been around ever since the RAND Corporation proposed placing rods on the tips of ICBMs in the 1950s… The "U.S. Air Force Transformation Flight Plan," published by the Air Force in November 2003, references "hypervelocity rod bundles" in its outline of future space-based weapons, and in 2002, another report from RAND, "Space Weapons, Earth Wars," dedicated entire sections to the technology's usefulness. The guided tungsten rods enter the atmosphere, protected by a thermal coating, traveling at 36,000 feet per second—comparable to the speed of a meteor. The result: complete devastation of the target, even if it's buried deep underground (HDBTs).

Materials, Propulsion and Fuels

Materials and propulsion are main drivers for cost, and there are some possible solutions on the horizon. Solutions proposed by Dr. Bushnell include Nano tube materials for weight savings,[122] advanced ablative materials for one-time use vehicles,[123] and breakthroughs in in Low Energy Nuclear Reaction (LENR) research could revolutionize high-speed materials for air-breathing vehicles in the next 15 to 20 years.[124] More research on possible LENR advances will accelerate hypersonic technology. Defense Industry leaders are also researching low-cost manufacturing solutions for ceramic-composite materials; a key enabler for large-scale production of hypersonic vehicles.[125]

Cheaper alternatives to a new engine capable of scramjet transition speeds also need to be explored.[126] One cost saving option could be a re-look at the SR-71 turbojet/ramjet type engine technology.[127] Additionally, water-injection thrust boosting techniques on current aircraft engines capable of Mach 2 could provide an inexpensive solution, and a cooling mechanism.[128][129] AFLR should also leverage the ADVENT engine program and PDE

[122] Interview with Dr. Bushnell, "Nano Tube structures have some 500 times the strength-to-weight of steel and overall proffer factors of 3-to-5-to-8 Dry weight reduction. Weight in Aerospace is EVERYTHING! However, these can withstand up to only 800 deg C heat (1500 Deg. F) so will need to be cooled or integrated with other materials. SEE ALSO, Dr. Charles Harris, AIAA SDM Conference "Opportunities for Next Generation Aircraft enabled by Revolutionary Materials." April 7 2011. Slide 3. Boron Nitrate Nano Tubes properties allow increased thermal conduction (approx. 600 W/Mk) and radiation protection

[123] Ibid. Bushnell states, Advanced ablators (NASA initiative) are still the best for the money for a one-time use vehicle and are far less expensive than Nano or composites. For more information see: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070014637_2007014752.pdf

[124]. Ibid. Bushnell goes on to state, "For Mach 7 ish A/B vehicles the MAJOR Tech Revolution is not materials, is Energetics. LENR is being worked, some 1,000 to 1,000,000 times Chemical Energy Density, Fuel fraction/ weight goes away. Not near term but may develop rapidly." More research is required, and not in the scope of this paper to address all the implications of LENR.

[125] Both Lockheed Martin and Boeing have initiatives in work to leverage low cost manufacturing.

[126] It takes speeds above Mach 3 to allow transition to a ram/scramjet.

[127] Wikipedia.org, "SR-71 Blackbird," http://en.wikipedia.org/wiki/SR-71_Blackbird. A unique hybrid, the engine can be thought of as a turbojet inside a ramjet. At lower speeds, the turbojet provided most of the compression and most of the energy from fuel combustion. At higher speeds, the turbojet largely ceased to provide thrust; instead, air was compressed by the shock cones and fuel burned in the afterburner. Air that is compressed by the inlet/shockwave interaction is diverted around the turbo machinery of the engine and directly into the afterburner where it is mixed and burned. This configuration is essentially a ramjet and provides up to 70% of the aircraft's thrust at higher Mach numbers

[128] Purdue University.edu, "Water Injection," https://engineering.purdue.edu/~propulsi/propulsion/jets/basics/water.html. The maximum power a turbine engine can output depends largely upon the density or weight of the flow of the gases through the engine. Therefore, when the atmospheric pressure decreases or ambient air temperature increases, there is a loss in thrust. The power output can be boosted or restored by cooling the airflow with water or coolant. When the water/coolant is sprayed into the compressor inlet, the temperature of the air is reduced, increasing the density of the compressor inlet air, and consequently, the thrust is increased

[129] Interview with Dr. Bradley Leland, Lockheed Martin. Water injection or Extended Operations of engines is an old technology used in the DARPA Rascal program and in a program called Peace Jack, using water injection on F-4 engines. The idea is to used existing engines, and water injection to increase thrust and extend the life of the engine, which under goes extreme stress at those speeds.

developments to find efficient, cost saving options. [130] Finally, though Mach 8 does not seem required or feasible today, a hydrogen fueled vehicle may become a viable solution in the future; this requires more research on hydrogen and alternative fuels to increase speed and range capabilities. Dr. Bushnell states advances in HEDM[131] propellants and LENR research could provide options to replace Hydrocarbon/Hydrogen fuel and provide enough energy for possible SSTO vehicles.[132]

Testing and Aircraft Configuration

While flight tests are important, more robust ground testing and simulation could help keep down R&D costs. Additionally, most proposed concepts are unmanned aerial systems. After recent events of a CIA drone captured in Iran, more research on the feasibility of large remotely piloted aircraft must follow.[133] Most importantly, in the take-off, air-refueling and landing phases of flight.

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[130] Defense Industry Daily.com, "ADVENT," http://www.defenseindustrydaily.com/the-advent-of-a-better-jet-engine-03623/
The Adaptive Versatile Engine Technology (ADVENT) program aims to develop and demonstrate inlet, engine, exhaust nozzle, and integrated thermal management technologies that enable optimized propulsion system performance over a broad range of altitude and flight velocity. ADVENT is a 5-year project that aims to produce a revolution in jet engine design. Imagine the jet equivalent of a car engine that could give you Formula One performance or sub-compact mileage as required. ADVENT-equipped aircraft would have extra-long range, but be able to switch quickly to high-speed power maneuvers and still be comparatively efficient. The new engine design will use adaptive fan blades and engine cores to generate high thrust when needed, and optimize fuel efficiency when cruising or loitering, in order to combine the best characteristics of high-performance and fuel-efficient jet engines.
PDE: An ideal PDE design can have a thermodynamic efficiency higher than other designs like turbojets and turbofans because a detonation wave rapidly compresses the mixture and adds heat at constant volume. Consequently, moving parts like compressor spools are not necessarily required in the engine, which could significantly reduce overall weight and cost

[131] Young et. al "Lazarus: A SSTO Hypersonic Vehicle Concept Utilizing RBCC and HEDM Propulsion Technologies," Authors state, The *Lazarus* vehicle concept is designed to meet the requirement to launch a small payload to orbital velocities with little notice and for a fraction of the cost of existing launch vehicles. This SSTO vehicle is accomplished through the use of rocket based combined cycle engine (RBCC) and high energy density material (HEDM) propellants. These engines combine the space based performance of traditional rockets with the atmospheric performance of ramjet/scramjet engines. Lazarus further improves on RBCC performance with the use of HEDM propellants. These advanced propulsion elements make the *Lazarus* launch vehicle both feasible and viable in today's highly competitive market. Dr. Bushnell states, " advances in HEDM could obviate most-to-all of the range benefits [factor of 2 for a length/ weight constrained air launched weapon] of the air breathers, at far less cost."

[132] Bushnell, "NASA and LENR," slide 8, 9, 11. LENR allows huge amounts of energy from a small reaction, has huge implications for aeronautics, and fuels; to include huge range increases, mitigates sonic boom because of the possibility of energy projected forward reduces shock strength and virtually lengthens the vehicle…allows lower weight and higher speed and protecting materials from heat. Note: More research is required and implications of LENR cannot be fully investigated in this paper.

[133] Above certain speeds the pilot will rely on autonomous flight controls, however, after losing a CIA Drone in Iran, I'm not sure many future USAF Generals will take the risk for fighter-sized or bomber-sized remotely piloted aircraft . This Author's opinion only. Miller, "Drone Belonged to CIA" http://www.washingtonpost.com/world/national-security/drone-belonged-to-cia-officials-y/2011/12/05/gIQAylYGYO_story.html The officials said Iran's military appears to be in possession of one of the more sensitive surveillance platforms in the CIA's fleet.

Final Thoughts

The Obama Administration acknowledged the increasing capability gap for conventional prompt global strike in the Defense Strategic Guidance, stating the U.S. is shifting focus to the Pacific region and will invest in capabilities to operate freely in anti-access environments.[134] The document reveals Obama's commitment to the LRS family of systems and the need to overcome the current limitations in his prompt global strike options; timeliness, and increasingly the ability to gain access to highly-defended target area. Although future predictions are difficult, this paper contends emerging counter-stealth technologies will continue to diminish advantages of LO techniques and deny space assets.

By prioritizing R&D dollars in hypersonic technology, the USAF could provide the President with critical and timely global strike options by 2035. Hypersonic cruise missiles, conventional PGS platforms like the HTV-2, and hypersonic Strike/Reconnaissance aircraft could enhance the LRS family of systems; providing deterrence, stand-off weapons, HDBT attack, and critical ISR missions. Investment in hypersonic technology will ensure U.S. technology dominance over foreign developers, and could transfer to other innovative technologies, to include a SSTO vehicle. Commenting on the current fiscal realities, General Schwartz, CSAF, stated recently, "Because our Air Force will become smaller, we must continue to invest in key technologies to ensure critical capabilities and gain access in any domain."[135]

[134] Defense Strategic Guidance Document, Jan 2012, pg. 2. The United States will continue to make the necessary investments to ensure that We maintain regional access and the ability to operate freely in keeping with our treaty obligations and with international law. Pg. 4. The document states; "The U.S. military will invest to ensure freedom of action in (A2/AD) environments. This will include implementing the Joint Operational Access Concept, sustaining our undersea capabilities, developing a new stealth bomber, improving missile defenses, and continuing efforts to enhance the resiliency and effectiveness of critical space-based capabilities." States such as China and Iran will continue to pursue asymmetric means to counter our power projection capabilities, while the proliferation of sophisticated weapons and technology will extend to non-state actors as well. *Accordingly, the U.S. military will invest as required to ensure its ability to operate effectively in anti-access and area denial (A2/AD) environments*.

[135] General Norton Schwartz, CSAF, Address to the Air War College, 23 Jan 2012.

The USAF and future administrations need to stay the course, be willing to invest and share some risk in order to reap the benefits of hypersonic flight.

Appendix A: Long Range Strike Family of Systems

Introduction

The purpose of this appendix is to provide a background to some of the trade-off decisions the Air Force made in regards to long range strike and prompt global strike. It explains the bomber gap, and leadership decisions which steered the USAF and AFRL away from hypersonics and towards a sub-sonic bomber, and finally a description of what the LRS family of systems program. Ultimately, considering the length of time it takes to field an aircraft system, I believe the LRS family of systems will be the main strike force in 2035.

Background

With an aging B-52 fleet and too few B-2s, the Air Force has been trying to address the "Bomber Gap" and the lack of a prompt global strike platform for years. Since 1999, Air Force leadership, AFRL, and Congress called for exhaustive studies on survivability, speed vs. stealth, range, feasibility and many other factors involved in developing a new bomber.[136] Additionally, by the 2003 Iraq war, legacy B-52 and B-1 bombers could not be used to hit targets in and around Bagdad until the integrated IAD "Super Missile Engagement Zone" or Super MEZ, could be rolled back significantly.[137] Air Force leadership, including Lt Gen T. Michael Moseley, the air boss for OIF and later CSAF, realized that future Combined Forces Air Component Commanders in 2010 or 2020 could not count on long-range airpower forces to hit all types of targets anywhere on the globe.[138]

[136] Studies reviewed include: Sustaining Americas Strategic Advantage in Long-Range Strike (2010), 2005-06 QDR, Future Air Force Needs for Survivability (2006), Time Critical Conventional Strike (2009), U.S. Conventional Prompt Global Strike (2008), ASC-99: Systems and Operational Implications for Choosing the Best Speed for Global Missions 1999, Air Force Bomber Road Map 1999,
[137] Grant, "Return of the Bomber, The Future of Long-Range Strike" 16
[138] Ibid. 16

Appraisals of the operating environment suggested future campaigns might need a much more survivable and persistent long-range strike system.[139] Of note, one of the Bush administration's top priorities was to carry out Prompt "non-nuclear" preemptive global strike against possible WMD production or proliferation.[140] The 2005 QDR reported the Air Force had no solution, and the priority became to achieve a new bomber by 2018, capable of, "penetrating airspace and maintaining persistence in an opposed or unopposed airspace" according to General Moseley.[141] Furthermore, by 2006 AFRL and the Institute for Defense Analyses concluded that hypersonic technology would not be mature enough to support a 2012 program start date.[142] However, the Air Force leadership agreed that technologies like directed energy and hypersonics were in the realm of the possible for 2035 and beyond.[143]

Filling the bomber gap with a long range strike platform failed to gain much momentum until very recently; probably due to a comprehensive study from the Center for Strategic and Budgetary Assessment office. This study named, Sustaining America's Strategic Advantage in Long-Range Strike, proposed four options; 1) defer a new bomber until after 2020 to allow for technology maturation, 2) build a stand-off non-stealthy bomber, 3) the priority should be to develop a penetrating bomber first while taking advantage of service lives of existing bombers for stand-off attack, 4) procuring one bomber to replace all Air Force bombers.[144] The Air Force seems to view option three as the best path, and in early 2011, Secretary of Defense Gates announced the beginning of the Long Range Strike Bomber program (LRS-B), replacing the previous Next Gen Bomber program he cancelled in 2009.[145]

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139 Grant, "Return of the Bomber," 16.
140 Ibid 18.
141 Ibid 19. Author cited testimony to Congress in March of 2006
142 Ibid 20. Gen Moseley Testimony to House Armed Services Committee, march 3 2006
143 Ibid 24.
144 Gunzinger, " Sustaining America's Strategic Advantage in Long-Range Strike," xiii
145 Majumdar, David, "Budget Shrinks; acquisition programs outlined," Air Force Times.com http://www.airforcetimes.com/news/2011/02/defense-air-force-budget-acquisition-021511w/

Conclusions: See also the main document for publically releasable conclusions

The LRS-B program will be a classified program utilizing a streamlined acquisition process focusing on off the shelf mature technologies. AFRL says the 80-100 optionally manned subsonic bombers will be part of the LRS family of systems, and reach operational capability in the mid-2020s before the aging fleet goes out of service.[146] The aircraft will leverage mature technologies like advanced stealth and EA techniques in hopes to keep the costs down. One can conclude, because of our current and future funding constraints, the LRS-B will be the main bomber force in 2035. One can assume spiral upgrades will increase LRS-B capability by 2035, but it remains to be seen if it will be able to penetrate the IADS of 2035. However, the LRS concept assumes a bomber cannot solve the prompt global strike problem alone. It must be forward-based and augmented with stand-off weapons. Advances in hypersonic weapons and aircraft could provide critical capabilities for the LRS family of systems by 2035.

The Obama administration in its 2012 budget request asked for $197 million and a total of $3.7 billion over five years to develop the new bomber. After the cancellation of a previous effort to build a new bomber in 2009, the service re-examined its options and concluded that the Long Range Strike Family of Systems should include not just a bomber, but Intelligence, Surveillance, Reconnaissance (ISR), Electronic Attack (EA), and communication portions of the program, said Maj. Gen. Alfred Flowers, the Air Force's deputy assistant secretary for budget. He added that there would be one type of airframe, but with different missions depending upon the payload. The service hopes to eventually buy between 80 and 100 of the new bombers, he added.

[146]Ibid 1. The largest new program in the research and development account is the Long Range Strike Family of Systems, the "centerpiece" of which is a long range, stealthy, penetrating, nuclear-capable optionally manned bomber. The Air Force hopes the new bomber will be operational by the "mid-2020s," said Pentagon Comptroller Robert Hale. The Air Force, however, has not fully fleshed out the exact requirements for the aircraft. Important decisions remain, including how the concept of "optional manning" will work. "Conceptually: optionally manned. To be determined: how that will work," Flowers said. The service hopes to eventually buy between 80 and 100 of the new bombers, he added.

Appendix B: Operational Analysis

Introduction

This appendix explores operational analysis of the advantages of speed. There is some debate as to the required speed for survivability against future threats, and this gives the reader an overview of the recent studies on speed and RCS vs. survivability. Most of the research is based on work done by Lockheed Martin OA experts. Next, this section looks at speed vs. today's SAM systems as well as future SAMs to try and predict the speed required. Finally, some conclusions are given, which are also available in main document.

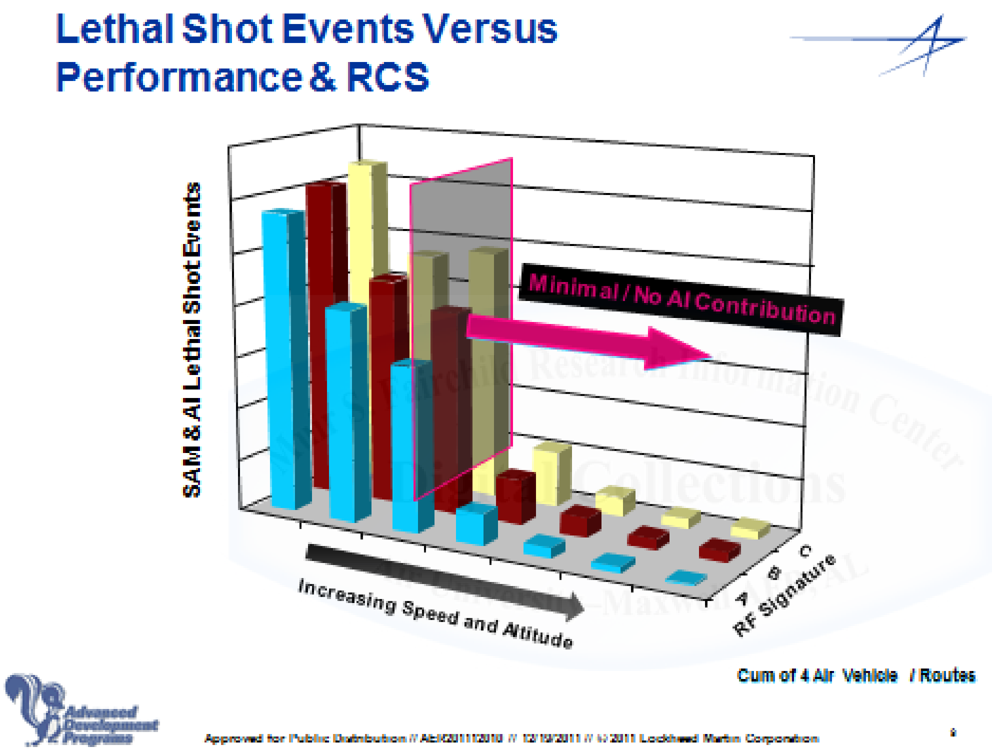
Speed Vs. Survivability

To answer the question of how much speed is required to survive the IADs of 2035 we can start by looking at recent operational analysis studies. For good reason however, most of these studies contain proprietary data and are export controlled. One study found on open source was the National Research Council's review of the Air Force Hy-tech program in 1998. This study looked at the vulnerability of a future hypersonic missile to surface-to-air missile.[147] They compared a Mach 6.5 and Mach 8 missile and found that the marginally higher vulnerability of the Mach 6.5 missile could be off-set by moderate reduction in RCS.[148] Other interviews with defense contractor operational analysis experts while researching for this paper all confirmed that the most important factors for survivability are: speed, altitude, and RCS.

There is a definite balance between speed, altitude and RCS or radar signature, and one can conclude from the literature that there is a perceived "knee in the curve" starting above Mach 5. Lockheed Martin Skunk Works operational analysis team provided me with the most telling

[147] Seebass et al, "Review and Evaluation of the Air Force Hypersonic Technology Program," Appendix C, pg. 54. They used an equation with radar performance parameter R (det), which is the maximum range for initial detection of a target with a RCS variable, missile speed, reaction time delay, and altitude to determine the range a hypothetical SAM could intercept a missile. The hypothetical system had a Radar range of 160 miles, Max target alt of 12,000ft, reaction time 8 seconds, average missile.
[148] Ibid 54

analysis on the balance between speed, altitude and RCS signature levels for survivability. The unclassified chart below compares three concepts of differing RCS levels (Z axis), concept A has less RCS and is more stealthy than concept B or C. As speed and altitude increase, along with better RCS signatures, the number of lethal SAM shots is significantly reduced.[149] The analysis concludes that hypersonic speed relaxes the need for LO technology to reduce RCS.

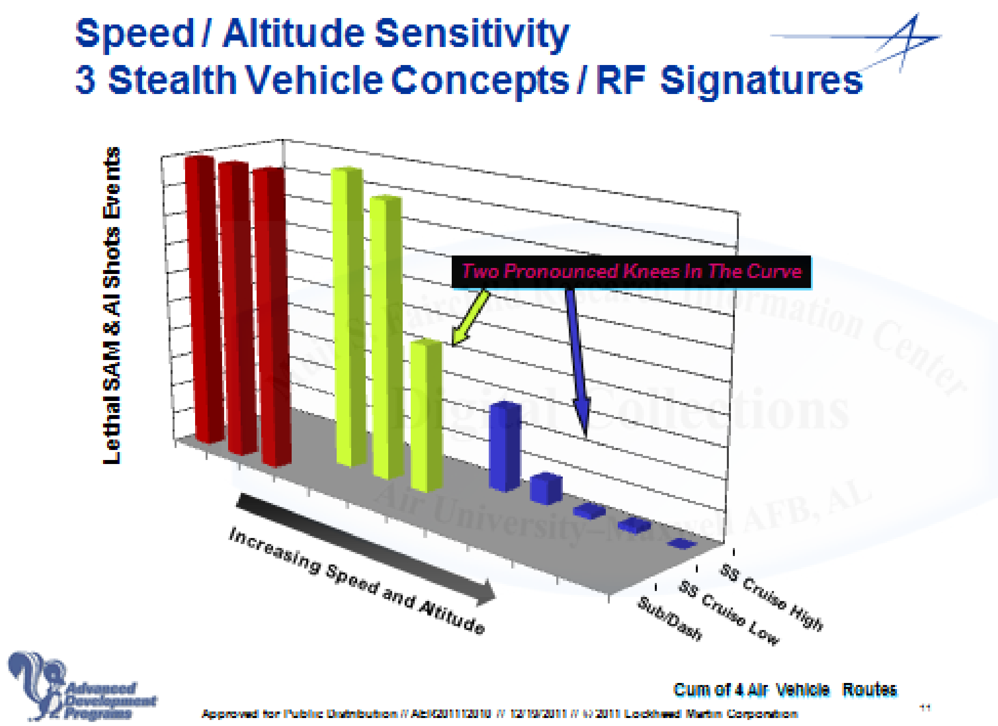


Appendix B Figure 19: Lethal Shot Vs. Performance and RCS

The Skunk Works study explored various aircraft concepts and survivability in Major Combat Operations (MCO) scenarios with robust IADS including air, sea, and land based threats. Their analysis points to two distinct knees in the curve; a high supersonic stealth aircraft starting about Mach 2.5-3.5, and a Mach 5-6 hypersonic cruise vehicle.[150] The study concluded that subsonic, or even low supersonic aircraft (Mach 2) will increasingly be vulnerable to future

[149] Ellrodt, "The Value of Speed/Altitude and Signature for Survivability," Oct 24, 2011, Slide 9.
[150] Notes from interview with Bernie Ellrodt, Senior Manager ADP, Operations Analysis, Skunk Works. These are my own conclusions from our discussions; he did not give any specific numbers on the record.

SAM systems like Chinese HQ-9, and highly capable 5th Generation Air Interceptors (AI) threats like the J-20. Also, hypersonic or high supersonic vehicles will minimize time in the threat SAM coverage's and impact from non-located or "Pop Up" SAMs. The Z axis on the slide below compares a subsonic cruise aircraft with low and high supersonic/hypersonic vehicles; and depicts two knees in the curve and the vulnerabilities to subsonic and low supersonic aircraft.[151]

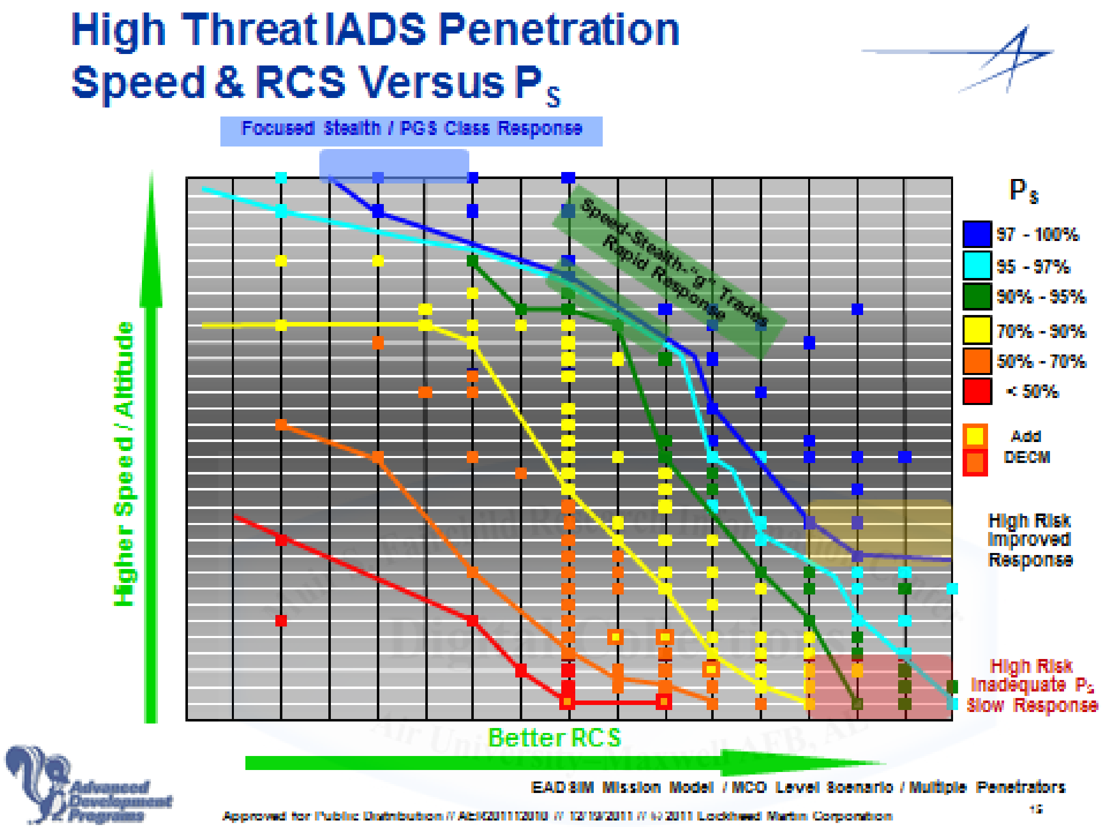


Appendix B Figure 20: Speed and Altitude Sensitivity

The most telling slide from the Skunk Works OA team integrates all the analysis into one chart seen below. The two options they propose are the hypersonic PGS vehicle with moderate stealth materials, and a high supersonic aircraft with significant stealth enhancements to reduce RCS. This chart best shows the balance between RCS, speed and Altitude for survivability (Ps). Overall, high speed and high altitude improves survivability by eliminating lower altitude threats

[151] Ellrodt, "The Value of Speed/Altitude and Signature for Survivability," Oct 24, 2011, Slide 11.

such as AAA and older SAM systems, sharply reducing strategic SAM shot opportunities, and largely eliminating AI capabilities.[152] Finally, the study concludes that hypersonic aircraft decrease the response time to attack critical time-sensitive targets or collect critical ISR.[153]



Appendix B Figure 21: Balance of Speed, RCS and Altitude

Future SAM Missile kinematics and ability to target Hypersonic Vehicles

One limiting factor to the Skunk Works analysis is that it did not seem to fully explore future missile systems and threats to hypersonic aircraft. Additionally, the study does not define what speed or RCS is required to survive. One can fairly easily calculate a ballpark speed required by looking at missile threat system data found in open source. Without regarding RCS

[152] Ellrodt, "The Value of Speed/Altitude and Signature for Survivability," Oct 24, 2011, Slide 18
[153] Ibid, slide 18

signature, a hypersonic system could simply avoid threats by either flying faster than the threat missile, or overflying the maximum threat missile altitude. As seen in the Table below, current missile threat systems range in speed from Mach 5 to Mach 7 and an altitude of just under 100,000 ft. I've simplified the data, since some of the SAM systems are known by different names. The HQ designation is the Chinese variant.

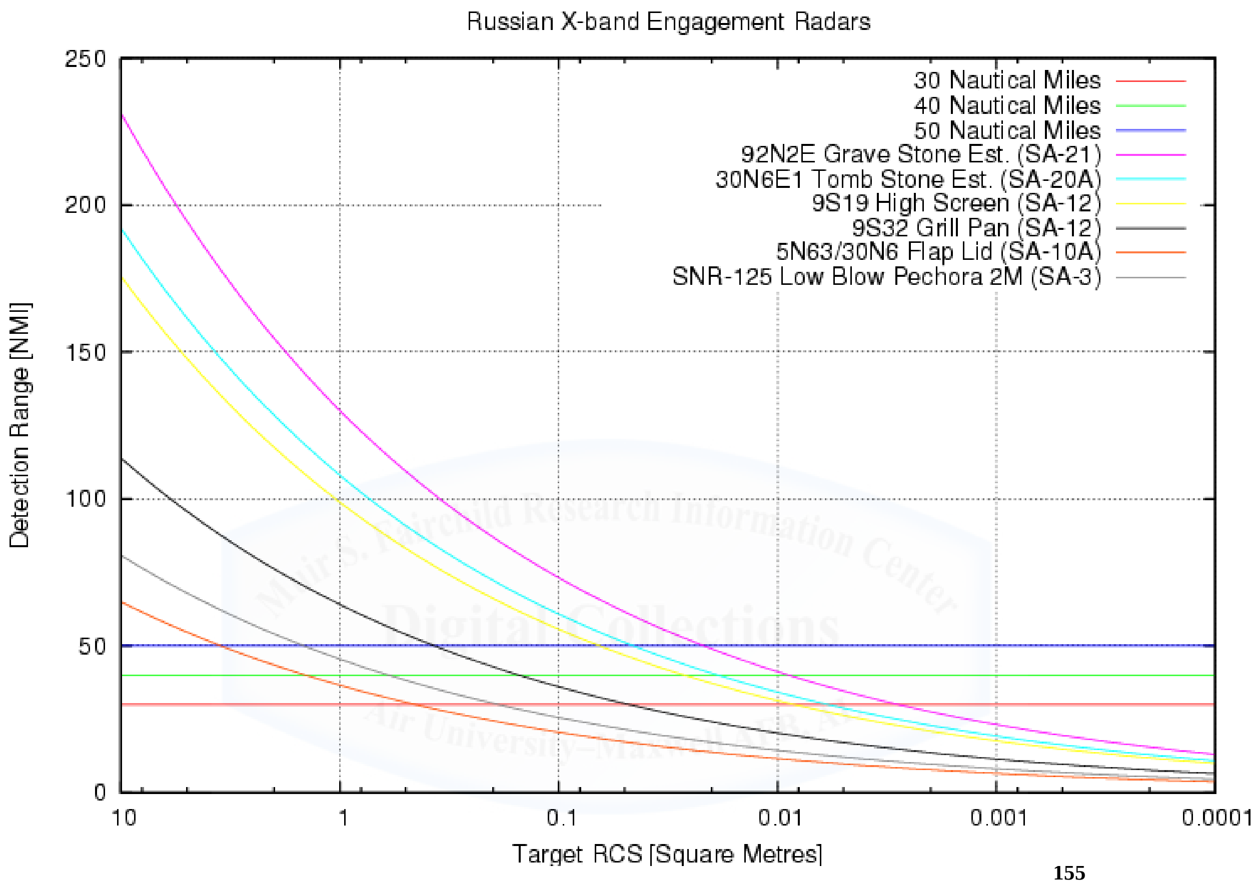
System Name(s)	Radar Detection Range	Missiles Used	Missile Max Alt	Max Missile Range	Max Speed
S300V, SA-12a Gladiator, SA-12b Giant, HQ-18	Approx. 300km	9M83 Gladiator 9M82 Giant	98,000ft 82,000ft	75-90km 100-200km	1.7 km/s (5 M) 2.4 km/s (7M)
S400, SA-20 Triumph	Approx. 400km	48N6/E 9M96	98,000ft 30km	250km 120km	2,000m/s (5.8M) 5 Mach
S400/SA-21 Growler		40N6 (long range missile) ABM type	185km?	400km	?
HQ-9/FT-2000	200km	Unnamed	98000ft	200km	4.2 Mach

Appendix B Table 3: Current SAM Capabilities[154]

Along with altitude and speed and altitude, the system detection range versus RCS is critical to determining how much speed might be required. Below is a table of Russian X-band radar detection range for various RCS. According to this, a 1m squared target (approximately the size of an F-16 RCS) can be seen out beyond 100nm. However, with moderate stealth shaping, an aircraft could achieve a 0.1 to .01 and move the detection range in to less than 50

[154] Taken from open source at: FAS.org, http://www.fas.org/nuke/guide/russia/airdef/s-300v.htm, Janes.com, Warfare.ru, http://www.warfare.ru/?lang=&linkid=1699&catid=264&topics=true&id=162, Wikipedia.com

miles. An aircraft like this traveling at Mach 5 or 50 miles a minute would be very difficult to find, ID and target, and complete missile fly-out time before the aircraft was out of range. And with just a small check turn the aircraft or missile could defeat most shots already in the air.



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Appendix B Figure 22: RCS vs. Detection Range

Conclusions: Also found in publically releasable section of the main document

Given the current threat missiles and detection range, it appears that Mach 5-6 with partial RCS reduction or a non-stealth aircraft flying at or above Mach 7 and above 100,000 feet will be able to fly into current robust IADs with near impunity.[156] However, future technology

[155] From Australian Air Power.net, http://www.ausairpower.net/APA-Engagement-Fire-Control.html#mozTocId853844
[156] This analysis is derived from data from the following sources. This analysis is derived from data from the following sources (See Appendix B for further discussion). Seebass et al, "Review and Evaluation of the Air Force Hypersonic Technology Program," Appendix C, pg. 54, Ellrodt, Bernie. "The Value of Speed/Altitude and Signature for Survivability," Lockheed Martin Skunk Works Power Point Presentation, Oct 24, 2011.

developments will increase IAD detection ranges allowing earlier intercepts on even hypersonic aircraft. Even so, OA experts believe future SAM systems like the S500 and HQ-18/19 are mainly focused on anti-ballistic missile intercepts, dealing with ballistic trajectories.[157] Additionally, air-defense missile kinematics for 100,000' intercepts becomes a design challenge; hypersonic cruise missiles and aircraft could provide severe targeting challenges for future IADs.[158] While long-range IR targeting may become a challenge, MISC experts deem the Directed Energy (DE) threat from China and Russia to be minimal and most likely unattainable by 2035.[159]

Annex to Appendix B: Export Controlled OA Data

Interviews with Mr., Bernie Ellrodt, Senior Manager Advanced Development Programs, Operational Analysis, Dr. Bradley Leland, Chief Engineer, Advanced Development Programs.
Tamplin, et al, "System And Operational Implications For Choosing the Best Speed for Global Missions." Kenne, et al, "Committee on Future Air Force Needs for Survivability
2 FAS.org, http://www.fas.org/nuke/guide/russia/airdef/s-300v.htm, Janes.com, Warfare.ru, http://www.warfare.ru/?lang=&linkid=1699&catid=264&topics=true&id=162, Australian Air Power.net, http://www.ausairpower.net/APA-Engagement-Fire-Control.html#mozTocId853844

[157] Interview with OA expert who would not go on the record. Also, from Janes.com, "HQ-18" Guidance is inertial with command updates and a semi-active radar terminal seeker. The maximum range is 100 km. The Chinese may be developing an improved version, but there has been no confirmation. An unconfirmed report in January 2010 stated that an intercept was made against an Anti-Ballistic Missile (ABM) target, and it is possible that this used an HQ-18 interceptor missile. (janes) http://articles.janes.com/articles/Janes-Strategic-Weapon-Systems/HQ-18-S-300V-China.html

[158] Notes from discussions with Mr. Bernie Ellrodt, Senior Manager Lockheed Martin Advanced Development Programs, Operational Analysis. Stated that future systems will have a difficult time completing an intercept above 100K, even if they become a faster missile, the thin air does not allow for much end-game maneuverability.

[159] Interview Dr. Wesley Walker, MSIC Systems Engineer for Directed Energy Weapons, 9 Jan 2012. Approved Public Released Statement: Foreign countries are developing directed energy weapons (DEW) – laser and high power microwave weapons – for air and space defense. Statements from Russian and Chinese military leaders indicate the development of these advanced weapons is a priority for both of their countries. These efforts will probably result in deployed air defense and anti-satellite DEW systems within the next 20 years. Defense against ballistic missiles or hypersonic vehicles is a much more stressing application for DEW systems, as these weapons are designed to withstand heavy heat loads and are much more resistant to DEW effects. The deployment of DEW systems with this mission in the next two decades is questionable at best, and in reality probably unlikely.

This data is export controlled, please contact Lt Col Letsinger at jonathan.letsinger@us.af.mil for access.

Conclusions: See Appendix B and Main Document for publically releasable Conclusions

Appendix C: Cost Analysis

Introduction

This appendix gives an idea of how overall aircraft costs are derived and how speed, range, and size are key drivers for cost. One can nearly predict the cost to develop an aircraft in terms of dollars per pound; empty weight and speed are the most significant variables in cost.[160] This appendix explores a study by the Aeronautical Systems Center (ASC) which analyzed six design concepts for a future bomber, from a subsonic 0.85, to an orbital Dyna-Soar type vehicle.

Cost Analysis

The Table below shows in 1999 dollars, the cost for development and total life-cycle costs for a fleet of 60 bombers. The bombers in the ASC study weighed over 420,000 lbs. fully fueled and loaded; the B-2 is 336,500lbs at max weight.[161] Of note, not only does cost increase as weight increases, but also as speed increase. For the 6 concepts from the study, cost went up as Mach increased. For comparison, the B-2 cost approximately $1.15Bil in 1997 dollars.[162]

Design Mach	Development	Production	Op/Sus	Total Life Cycle Costs
0.85	15	18	26	$59B
2.4	17	20	28	$65B
4.0	22	28	31	$81B
7.0	29	32	33	$94B
11.0	34	35	35	$104B
26.0	31	40	37	$107B

Appendix D Table1: Design Costs[163]

[160] Interview with Dr. Jim Miller, Chief, High Speed Aerodynamic Configuration branch, AFRL. Stated you can cost out aircraft procurement by the pound. Also found in Hess and Romanoff, "Aircraft Airframe Cost Estimating Relationships: Study Approach and Conclusions, http://www.rand.org/pubs/reports/2006/R3255.pdf figure 15, pg. 45

[161] Air Force Fact Sheet. "B-2 Spirit" http://www.af.mil/information/factsheets/factsheet.asp?fsID=82. Max weight 336, 500 lbs.

[162] Ibid Unit **cost:** Approximately $1.157 billion (fiscal 98 constant dollars).

[163] Tamplin, et al, "System And Operational Implications For Choosing the Best Speed for Global Missions," 95. 60 units, 427,000lb manned aircraft, 32,000lb payload, refuelable.

The study looked at range, survivability, sortie rates, tanker requirements, and life cycle costs among other things to rank the vehicles. The subsonic concept ranked high in this study, mainly because of the cost and an unrefueled range of 13,000 miles.[164] The Mach 7 and Orbital vehicle also ranked high, but the Mach 11 system was considered infeasible due to the liquid hydrogen fuel requirements and limitations. The study did not examine stand-off weapons. Overall, it seemed this study helped steer the Air Force away from a hypersonic bomber due to all the unknowns and perceived risks at the time. However, the Air Force and DARPA continue to look at the feasibility of hypersonic vehicles in current program research.

Conclusions: See Main Document for Cost Analysis Conclusions releasable to the public

[164] Tamplin, et al, "System And Operational Implications For Choosing the Best Speed for Global Missions," 110.

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